Technical Report on Interpretation of the Electrocardiogram (ECG) Signal using Formal Methods

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Abstract

Today an evidence-based medicine has given number of medical practice clinical guidelines and protocols. Clinical guidelines systematically assist practitioners with providing appropriate health care for specific clinical circumstances. However, a significant number of guidelines and protocols are lacking in quality. Indeed, ambiguity and incompleteness are more likely anomalies in medical practices. From last few years, many researchers have tried to address the problem of protocol improvement in clinical guidelines, but results are not sufficient since they believe on informal processes and notations. Our objective is to find anomalies and to improve the quality of medical protocols using well known formal techniques, such as EVENT B. In this report, we use the EVENT B modeling language to capture guidelines for their validation. We have established a classification of possible properties to be verified in a guideline. Our approach is illustrated with a guideline which published by the National Guideline Clearing House (NGC) and AHA/ACC Society. Our main contribution is to evaluate real-life medical protocols using refinement based formal method like EVENT B for improving quality of the protocols. Refinement based formalisation is very easy to handle any complex medical protocols. For this evaluation we have selected a real-life reference protocol (ECG Interpretation) which covers a wide variety of protocol characteristics related to the several heart diseases. We formalise the given reference protocol, verify a set of interesting properties of the protocol and finally determine anomalies. Our main results are: to formalise an ECG interpretation protocol for diagnosing the ECG signal in optimal way; to discover an hierarchical structure for the ECG interpretation efficiently using incremental refinement approach; a set of properties which should be satisfied by medical protocol; verification proofs for the protocol and properties according to the medical experts; and perspectives of the potentials of this approach. Finally, we have shown the feasibility of our approach for analysing medical protocols.

Keywords: Electrocardiogram (ECG), Heart, Medical protocol, Abstract model, EVENT B, Event-driven approach, Proof-based development, Refinement.

1. Introduction

A promising and challenging application area for the application of formal methods is a clinical decision making, as it is vital that the clinical decisions are sound. In fact, ensuring safety is the primary preoccupation of medical regulatory agencies. Medical guidelines are "systematically developed statements to assist practitioners and patient decisions about appropriate health care for specific circumstances" [1, 2]. Based on updated empirical evidence, the medical protocols provide clinicians with health-care testimonial and facilitate the spreading of high-standard practices. In fact, this way represents that adherence to protocols may reduce the costs of care upto 25% [2]. In order to reach their potential benefits, protocols must fulfill strong quality requirements. Medical bodies worldwide have made efforts in this direction, e.g. elaborating appraisal documents that take into account a variety of aspects, of both protocols and their development process. However, these initiatives are not sufficient since they rely on informal methods and notations. Informal methods and notations have not any mathematical foundations.

We are concerned with a different approach, namely the quality improvement of medical protocols through formal methods. In this report we have given on our experiences in the formalisation and verification of a medical protocol for diagnosis of the Electrocardiogram (ECG). ECG signals are too complex for diagnosis. All kinds of diseases related to the heart are predictable using 12-lead ECG signals. A high number of medical guidelines for the ECG interpretation have been published in the literature and on internet, making them more accessible. Currently, protocols are described using a combination of different formats, e.g. text, flow diagrams and tables. These approaches are used in form of informal processes and notations for analysing the medical protocols, which are not sufficient for medical practices. As a result, the ECG interpretation guidelines and protocols[1] still contain ambiguous, incomplete or even inconsistent elements.

The idea of our work is translating informal descriptions of the ECG interpretation into a more formal language, with the aim of analysing a set of properties of the ECG protocol. In addition to the advantages of such kind of formal verification, making these descriptions more formal can serve to expose problematic parts in the protocols.

Formal methods have well structure representation language with clear and well-defined semantics, which can be used for taxonomy verification of clinical guidelines and medical protocols. The representation language represents guidelines and protocols explicitly and in a non-ambiguous way. The process of verification using formal semantic representation of guidelines and protocols allow the determination of consistency and correctness.

Formal modelling and verification of medical protocols have been carried out as a case study to assess the feasibility of this approach. Throughout our case study, we have shown formal specification and verification of medical protocols. The ECG interpretation protocol is very complex, ambiguous, incomplete and inconsistent. For modeling the ECG interpretation, we consider five basic objectives as follows:

- To establish a unified theory and proper guidelines for analysising the

[1] Guideline and protocol are different terms. The term protocol is used to represent a specialised version of a guideline. In this report we use them indistinctively.

ECG.

- To find ambiguity, incompleteness and inconsistency in the ECG protocol.
- Requirements and metrics for certifiable assurance and safety.
- To build a comprehensive and integrated suite of tools for the ECG interpretation supporting prediction for heart diseases.
- Refinement-based formal development to achieve less error-prone models, easier specification for the ECG interpretation protocol and reuse of such specification for further diagnosis.

The contribution of our report is to give a complete idea of the formal development of ECG interpretation protocol and we have discovered a hierarchical structure for the ECG interpretation efficiently using incremental refinement approach. Same approach can be also applied for developing a formal model of protocol of any other disease. Our approach is based on the EVENT B [3, 4] modeling language which is supported by the RODIN platform integrating tools for proving models and refinements of models. Here we present an incremental proof-based development to model and verify such interdisciplinary requirements in EVENT B [3, 4]. The ECG interpretation models must be validated to ensure that they meet requirements of the ECG protocols. Hence, validation must be carried out by both formal modeling and medical domain experts.

We have used the general formal modeling tool like Event-B [4] for modeling a complex medical protocol related to diagnoses of ECG signal. To apply a refinement based technique to model a medical protocol is our main objective. Event-B supports refinement technique. The refinement supported by the RODIN [5] platform guarantees the preservation of safety properties. The safety properties are detection of actual disease under certain conditions. The behavior of the final system is preserved by an abstract model as well as in the correctly refined models. Proof-based development methods [4] integrate formal proof techniques in the development of software systems. The main idea is to start with a very abstract model of the (closed) target system under development. Details are gradually added to this first model by building a sequence of more concrete events. The relationship between two successive models in this sequence is *refinement* [4, 6]. This technique is used to model a medical protocol more rigorously based on formal mathematics, which helps to find the anomalies and provide the consistency and correctness of the medical protocol. The current work intends to explore those problems related to the modeling of the ECG protocols. The formalization of the ECG protocol is based on original protocol and all safety properties and related assumptions are verified with the medical experts. Moreover, an incremental development of the ECG interpretation protocol model helps to discover the ambiguous, incomplete or even inconsistent elements in current the ECG interpretation protocol.

The outline of the remaining report is as follows. Section 2 contains related work. The modeling framework is presented in Section 3. Section 4 presents selection of medical protocol for formalisation. We give a brief outline of the ECG in Section 5. In Section 6, we explore the incremental proof-based formal development of the ECG interpretation protocol. The verification results are analyzed by statistical proof and lessons learned in Section 7. Finally, in Section 8, we conclude the report and discuss future challenges.

2. Related Work

Section 2 currently presents ongoing research work related to computer-based medical guidelines and protocols for clinical purposes. From past few years many languages have been developed for representing medical guidelines and protocols using various levels of formality based on experts requirements. Although we have used EVENT B modeling language for guidelines and protocol representation in our case study. Various kinds of protocol representation languages like Asbru [7, 2], EON [8], PROforma [9] and others [10, 11] are used to represent a formal semantics of guidelines and medical protocols.

Clinical guidelines are useful tools to provide some standardization and helps for improving the protocols. A survey paper [12] presents benefits and comparison through an analysis of different kinds of systems, which are used by clinical guidelines. This paper cover a wide scope of clinical guideline related literatures and tools, which are collected from the medical informatics area.

A approach for improving guidelines and protocols is by evaluating the physician. Evaluation process involves scenario and evidence based testing which compares the actions. The actions are performed by physicians to handle particular patient case using testimonials that are prescribed by the guidelines [13]. When results of the actions deviate, evaluation process can either focused on the explanation or alternatively provide some valuable feedback for improving guidelines and protocols [14]. An intentions based evaluation process are deduced by the physicians from both the patient data and the performed actions. These are then verified against the intentions reported in the guideline.

Automated quality assessment of clinical actions and patient outcomes is another area of related work, which is used to derive structured quality indicators from formal specifications of guidelines. This technique is used in decision support [15]. Such kinds of indicators is used as formal properties in our work that guideline must comply with.

Decision-table based techniques for the verification and simplification of guidelines are presented by Shiffman et al. [16, 17]. Basic idea behind this approach is to describe guidelines as condition/action statements: *If the antecedent circumstances exist, then one should perform the recommended actions* [17]. Completeness and consistency are two main properties for verification, when guidelines and protocols are expressed in terms of decision-table. Again, these properties are internal coherence properties, whereas we are focused on domain specific properties.

Formal development of the guidelines and protocols using clinical logic may be incomplete or inconsistent. This problem is tackle by Miller et al. [18]. *If "if-then" rules are used as representation language for guidelines, incompleteness* *means that there are combinations of clinically meaningful conditions to which the system (guideline) is not able to respond* [18]. The verification of rule-based clinical guidelines using semantic constraints is supported by the commander tool. This tool is able to identify clinical conditions where the rules are incomplete. Miller et al. [18] were able to find a number of missing rules in various case studies of guidelines and protocols.

Guidelines enhancement is represented through adoption of an advanced Artificial Intelligence techniques [19]. The paper has proposed an approach for verification of the guideline, which is based on the integration of a computerized guidelines management system with a model-checker. They have used SPIN model checker [20, 21] for executing and verifying medical protocols or guidelines. A framework for authoring and verification of clinical guidelines is provided by Beatriz et al [22]. The verification process of guideline is based on combined approach of Model Driven Development (MDD) and Model Checking [21] to verify guidelines against semantic errors and inconsistencies. UML [23, 24] tool is used for modeling the guidelines and a generated formal model is used as the input model for a model checker.

Jonathan et. al[25] have proposed a way to apply formal methods, namely interactive verification to improve the quality of medical protocols or guidelines. They have applied this technique for the management of jaundice in newborns based on guidelines of American Academy of Pediatrics. This paper includes formalisation of the jaundice protocol and verify some interesting properties. Simon et. al [26] have used the same protocol for improvement purpose using a modeling language Asbru, temporal logic for expressing the quality requirements, and model checking for proof and error detection.

Applying formal approach for improving medical protocol is one major area of research, which helps to the medical practitioners for improve the quality of patient care. A project Protocure [27] is an European project, which is carried out by five different institutions. Main objective of this project is for improving medical protocol through integration of formal methods. Main motivation of this project to identify anomalies like ambiguity and incompleteness in medical guidelines and protocols. Presently all medical protocols and guidelines are in text, flow diagrams and tables formats, which are easily understandable by my medical practitioners. But these are incomplete and ambiguous due to lack of formal semantics. The idea of using formal methods is to uncover these ambiguous, incomplete or even inconsistent parts of the protocols, by defining all the different descriptions more precisely using a formal language and to enable verification. Mainly the researchers have used Asbru [2] language for protocol description and KIV for interactive verification system [28].

Asbru [2] is a main modeling language for describing medical protocol and formal proof of the medical protocol is possible through KIV interactive theorem prover [28]. Guideline Markup Tool(GMT) [29] is an editor that helps translating guidelines into Asbru. An additional functionality of the tool is to define relations between the original protocol and its Asbru translation with a link macro [29]. Asbru language is used for protocol description and Asbru formalizations are translated into KIV. Asbru is considered as a semi-formal language to support the tasks necessary for protocol-based care. It is called a semi-formal language because its semantics, although more precise than in other protocol representation languages, are not defined in a formal way . This semi-formal quality makes Asbru suitable for an initial analysis but not for systematic verification of protocols [30].

According to our literatures survey, none of the medical protocol tool exists, which is based on purely formal semantics. In this study, we have tried to model a medical protocol, completely based on formal semantics and to check various anomalies. To overcome from the existing problems [31, 30] in area of development of medical protocols, we have used the general formal modeling tool like Event-B [4] for modeling a complex medical protocol related to diagnoses of ECG signal. The main objective to use Event-B modeling language is to model medical protocol using refinement approach. Medical protocols are very complex and to model a complex protocol, a refinement approach is very helpful, which introduced peculiarity of the protocols in an incremental way. This technique is used to model a medical protocol more rigorously based on formal mathematics, which helps to find the anomalies and provide the consistency and correctness of the medical protocol.

3. The Event B modeling framework

This section presents overview of Event B modeling language for understanding the developed formal specification of the ECG interpretation protocol. We have used Event B in this development, while a model developer can use any modeling tool like Z, VDM and ASM etcetera for specifying a medical protocol. These modeling tools help to find anomalies in medical protocol, and to check the consistency and correctness of the medical protocol. For developing a medical protocol using such kinds of modeling tools, a modeler has required a good understanding of logic.

We summarize the concepts of the Event B modeling language developed by Abrial [3, 4] and indicate the links with the tool called RODIN [5]. The modeling process deals with various languages, as seen by considering the triptych of Bjoerner [32, 33]: $\mathcal{D}, \mathcal{S} \longrightarrow \mathcal{R}$. Here, the domain $\mathcal{D}$ deals with properties, axioms, sets, constants, functions, relations, and theories. The system model $\mathcal{S}$ expresses a model or a refinement-based chain of models of the system. Finally, $\mathcal{R}$ expresses requirements for the system to be designed. Considering the Event B modeling language, we notice that the language can express *safety* properties, which are either *invariants* or *theorems* in a machine corresponding to the system. Recall that two main structures are available in Event B :

- Contexts express static information about the model.
- Machines express dynamic information about the model, invariants, safety properties, and events.

A Event B model is defined either as a context or as a machine. The triptych of Bjoerner [32, 33] $\mathcal{D}, \mathcal{S} \longrightarrow \mathcal{R}$ is translated as follows: $\mathcal{C}, \mathcal{M} \longrightarrow \mathcal{R}$, where $\mathcal{C}$ is a context, $\mathcal{M}$ is a machine and $\mathcal{R}$ are the requirements. The relation $\longrightarrow$ is defined to be a logical satisfaction relation with respect to an underlying logico-mathematical theory. The satisfaction relation is supported by the RODIN platform. A machine is organizing events modifying state variables and it uses static informations defined in a context. These basic structure mechanisms are extended by the refinement mechanism which provides a mechanism for relating an abstract model and a concrete model by adding new events or by adding new variables. This mechanism allows us to develop gradually EVENT B models and to validate each decision step using the proof tool. The refinement relationship should be expressed as follows: a model M is refined by a model P, when P is simulating M. The final concrete model is close to the behavior of real system that is executing events using real source code. We give details now on the definition of events, refinement and guidelines for developing complex system models.

3.1. Modeling actions over states

The event-driven approach [3, 4] is based on the B notation. It extends the methodological scope of basic concepts to take into account the idea of *formal models*. Briefly, a formal model is characterized by a (finite) list x of *state variables* possibly modified by a (finite) list of *events*, where an invariant $I(x)$ states properties that must always be satisfied by the variables x and *maintained* by the activation of the events. In the following, we summarize definitions and principles of formal models and explain how they can be managed by tools [34, 35, 5].

Generalized substitutions are borrowed from the B notation. They provide a means to express changes to state variable values. In its simple form $x := E(x)$, a generalized substitution looks like an assignment statement. In this construct, x denotes a vector built on the set of state variables of the model, and $E(x)$ denotes a vector of expressions. Here, however, the interpretation we shall give to this statement is not that of an assignment statement. We interpret it as a *logical simultaneous substitution* of each variable of the vector x by the corresponding expression of the vector $E(x)$. There exists a more general normal form of this, denoted by the construct $x :|(P(x,x'))$. This should be read as *x is modified in such a way that the value of x afterwards, denoted by x', satisfies the predicate $P(x,x')$*, where x' denotes the *new value* of the vector and x denotes its *old value*. This is clearly nondeterministic in general.

An event has two main parts, namely, a *guard*, which is a predicate built on the state variables, and an *action*, which is a generalized substitution. An event can take one of three normal forms. The first form (BEGIN $x :|(P(x,x')$ END) shows an event that is not guarded, being therefore always enabled and semantically defined by $P(x,x')$. The second form (WHEN $G(x)$ THEN $x :|(Q(x,x'))$ END) and third form (ANY t WHERE $G(t,x)$ THEN $x :|(R(x,x',t))$ END) are guarded by a guard that states the necessary condition for these events to occur. The guard is represented by WHEN $G(x)$ in the second form, and by ANY t WHERE $G(t,x)$ (for $\exists t \cdot G(t,x)$) in the third form. We note that the third form defines a possibly nondeterministic event where t represents a vector of distinct local variables. The *before–after* predicate $BA(x, x')$, associated with each of the three event types, describes the event as a logical predicate expressing the relationship linking the values of the state variables just before (x) and just after (x') the *execution* of event e. The second and the third forms are semantically equivalent to $G(x) \ \wedge \ Q(x, x')$ resp. $\exists t \cdot (G(t, x) \ \wedge \ R(x, x', t)$.

Proof obligations
• (INV1) $Init(x) \ \Rightarrow \ I(x)$
• (INV2) $I(x) \ \ \wedge \ \ BA(e)(x, x') \ \Rightarrow \ I(x')$
• (FIS) $I(x) \ \ \wedge \ \ \mathsf{grd}(e)(x) \ \Rightarrow \exists y.BA(e)(x, y)$

Table 1: Event B proof obligations

Proof obligations (INV 1 and INV 2) are produced by the RODIN tool [5] from events to state that an invariant condition $I(x)$ is preserved. Their general form follows immediately from the definition of the before-after predicate $BA(e)(x, x')$ of each event e (see Table 1). Note that it follows from the two guarded forms of the events that this obligation is trivially discharged when the guard of the event is false. Whenever this is the case, the event is said to be *disabled*. The proof obligation FIS expresses the feasibility of the event e with respect to the invariant I.

3.2. Model refinement

The refinement of a formal model allows us to enrich the model via a *step-by-step* approach and is the foundation of our correct-by-construction approach [36]. Refinement provides a way to strengthen invariants and to add details to a model. It is also used to transform an abstract model to a more concrete version by modifying the state description. This is done by extending the list of state variables (possibly suppressing some of them), by refining each abstract event to a corresponding concrete version, and by adding new events. The abstract (x) and concrete (y) state variables are linked by means of a *gluing invariant* $J(x, y)$. A number of proof obligations ensure that (1) each abstract event is correctly refined by its corresponding concrete version, (2) each new event refines *skip*, (3) no new event takes control for ever, and (4) relative deadlock freedom is preserved. Details of the formulation of these proofs follows.

We suppose that an abstract model AM with variables x and invariant $I(x)$ is refined by a concrete model CM with variables y and gluing invariant $J(x, y)$. If $BA(e)(x, x')$ and $BA(f)(y, y')$ are respectively the abstract and concrete before–after predicates of the same event, e and f respectively, we have to prove the following statement, corresponding to proof obligation (1):

$$\boxed{I(x) \ \wedge \ J(x, y) \ \wedge \ BA(f)(y, y') \ \Rightarrow \ \exists x' \cdot (BA(e)(x, x') \ \wedge \ J(x', y'))}$$

Now, proof obligation (2) states that $BA(f)(y, y')$ must refine *skip* ($x' = x$), generating the following simple statement to prove (2).

$$\boxed{I(x) \ \wedge \ J(x,y) \ \wedge \ BA(f)(y,y') \ \Rightarrow \ J(x,y')}$$

In refining a model, an existing event can be refined by strengthening the guard and/or the before-after predicate (effectively reducing the degree of non-determinism), or a new event can be added to refine the *skip* event. The feasibility condition is crucial to avoiding possible states that have no successor, such as division by zero. Furthermore, this refinement guarantees that the set of traces of the refined model contains (up to stuttering) the traces of the resulting model. The refinement of an event e by an event f means that the event f simulates the event e.

The Event B modeling language is supported by the RODIN platform [5] and has been introduced in publications [4, 3], where there are many case studies and discussions about the language itself and the foundations of the Event B approach. The language of *generalized substitutions* is very rich, enabling the expression of any relation between states in a set-theoretical context. The expressive power of the language leads to a requirement for help in writing relational specifications, which is why we should provide guidelines for assisting the development of Event B models.

4. Selection of medical protocol

Concerning the protocols that are the object of our study, we have selected the ECG interpretation that cover a wide range of protocol characteristics related to the heart diseases. All kinds of medical guidelines and protocols differ from each others along several dimensions, which can be refer to the contents of the protocols or to its form. General practitioners (GPs), nurses and a large group of people related to this domain[2] are the *most important target users* of guidelines and protocols, and main aspects of clinical practice is to cover *diagnosis* as well as helps in treatments. Medical guidelines and protocols, which are used by general practitioners and nurses, are also characterized by time dimensions; short time-span protocols; long-time span protocols. The form of guidelines and protocols are related to textual descriptions. Sometimes it is also represented textual form as well as combination with *tables* and *flowcharts*.

The ECG interpretation protocol [37, 38] aims at cardiologist as well as GPs and covers both diagnosis and treatment over a long period of time. The ECG interpretation protocol can be considered more precisely: one is in daily use by cardiologist and the other is included in the repository of the National Guideline Clearinghouse(NGC), American College of Cardiology/American Heart Association (ACC/AHA). Basic standard for inclusion in the NGC and ACC/AHA are that guidelines and protocols contain well structured meaningful informations and systematically developed statements. The contents are produced under the supervision of medical specialty associations. It should be also based on literatures, reviewed and revised within the last 5 years. Furthermore, the ECG

[2] http://www.guideline.gov/

interpretation protocol has been published in a peer-reviewed scientific journal. In summary, the chosen protocol covers different aspects while fulfilling high quality standards, which are good criteria for selection of our case study.

In the following sections we will use the ECG interpretation protocol as the main example in our explanations, and we therefore give a brief description of this protocol. Electrocardiogram (ECG or EKG) interpretation is a common technique to trace abnormalities in the heart system and various levels of tracing help to find severe diseases. The guideline is more then 100 pages document, which contains knowledge in various notations: the main text; a list of factors to be considered when assessing an abnormality in heart ECG signal and a flowchart describing the steps in the ECG interpretation protocol. The protocol consists of an evaluation (or diagnosis) part and a treatment part, to be performed in successive way. During the application of guidelines and protocols, as soon as the possibility of a more serious disease is uncovered, the recommendation is to leave the protocol without any further action.

5. Basic overview of Electrocardiogram (ECG)

The electrocardiogram (ECG or EKG) [37, 39] is a diagnostic tool that measures and records the electrical activity of the heart precisely in form of signals. Clinicians can evaluate the conditions of a patient's heart from the ECG and perform further diagnosis. Analysis of these signals can be used for interpreting diagnosis of a wide range of heart conditions and predict related diseases. ECG records are obtained by sampling the bioelectric currents sensed by several electrodes, known as leads. A typical one-cycle ECG tracing is shown in Fig.-1. Electrocardiogram term is introduced by Willem Einthoven in 1893 at a meeting of the Dutch Medical Society. In 1924, Einthoven received the Nobel Prize for his life's work in developing the ECG [37, 40, 41, 38, 42, 43, 39, 44].

The normal electrocardiogram (ECG or EKG) is depicted in Fig.-1. All kinds of segments and intervals are represented in this ECG diagram. Depolarization and repolarization of ventricular and atrial chambers are presented by deflection of the ECG signal. All these deflections are denoted by alphabetic order (P-QRS-T). Letter P indicates atrial depolarization and the ventricular depolarization is represented by QRS complex. The ventricular repolarization is represented by T-wave. Atrial repolarization appears during the QRS complex and generates very low amplitude signal which cannot be uncovered from the normal ECG signal.

5.1. Differentiating the P-, QRS- and T-waves

Sequential activation, depolarization, and repolarization are deflected distinctly in ECG due to anatomical difference of the atria and the ventricles. Even all sequences are easily distinguishable when they are not in correct sequence: P-QRS-T. QRS-complex are easily identifiable between P- and T-wave because it has characteristic waveform and dominating amplitude. This amplitude is about 1000 μm in a normal heart and can be much greater in ventricular hypertrophy. Normal duration of the QRS-complex is 80-90 ms. In case of non-existence of atrial hypertrophy, an amplitude and duration of P-wave is about 100 μm and 100 ms, respectively. The T-wave has about twice of the amplitude and duration of the P-wave. The T-wave can be differentiated from the P-wave by observing that the T-wave follows the QRS-complex after about 200 ms. In ECG signal several parameters are used to evaluate the conditions of a patient's heart from the ECG. The parameters are: PR-interval, P-wave, QRS duration, Q-wave, R-wave, ST-segment, T-wave, Axis, QT-interval. All these parameters have several different characteristics that are used for diagnosis.

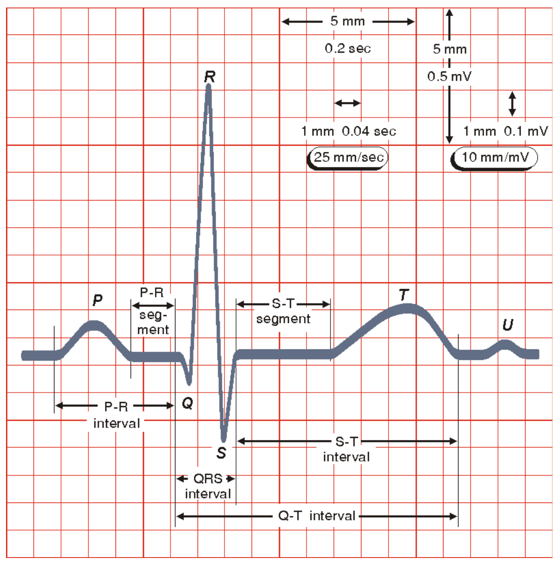

Figure 1: A typical one-cycle ECG tracing [44]

6. Formal development of the ECG interpretation

6.1. Abstract model : Assessing rhythm and rate

We begin by defining the Event B context. The context uses sets and constants to define axioms and theorems. Axioms and theorems represent the logical theory of the system. The logical theory is the static properties and properties of the target system. In the context, we define constants *LEADS*, *HState* and *YesNoState* that are related to the enumerated set of ECG leads, normal and abnormal states of the heart and yes-no states, respectively. These constants are extracted from the ECG interpretation protocol [37, 41, 43, 39]. The standard 12-lead electrocardiogram is a representation of the heart's electrical activity recorded from electrodes on the body surface. The set of leads is represented as $LEADS = \{I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, V6\}$. Normal and abnormal states of heart are represented by $HState = \{OK, KO\}$ and yes-no

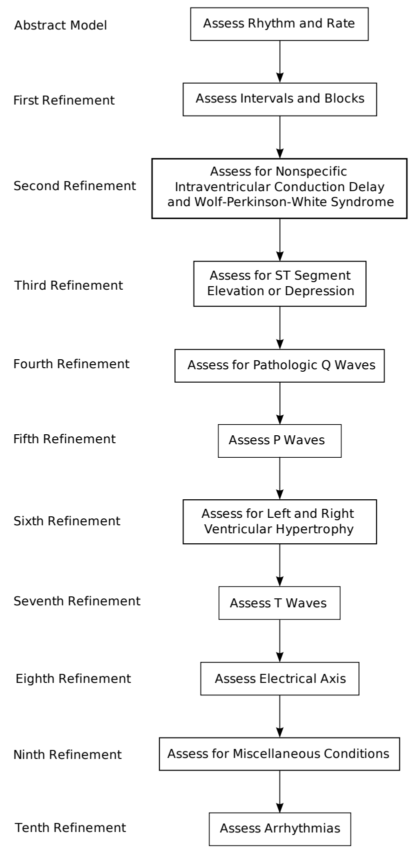

Figure 2: ECG interpretation protocols refinements

states are represented by $YesNoState = \{Yes, No\}$. Fig.-2 represents a view of incremental formal development of the ECG interpretation protocol. In our development process some refinements are decomposed into several refinements for the simplicity. Every refinement level introduces a *diagnosis* criteria for different components of the ECG signal and each new criteria helps to analyse particular a set of diseases. Particular set of diseases is introduced in multiple context related to each refinement.

Figure 3 shows an abstract representation of a *diagnostic-based* system development. Root circle (?) represents set of conditions for testing any particular disease abstractly. The possible abstract outcomes of diagnosis criteria are in form of OK and KO, which are represented by two branches. KO represents that diagnosis criteria has found some conditions for further testing, while OK represents absence of any disease. Dash line of circles and arrows represent next level of refinement for further analysing any particular diseases according to guidelines and protocols.

Our abstract Event B model of the ECG interpretation protocol assess

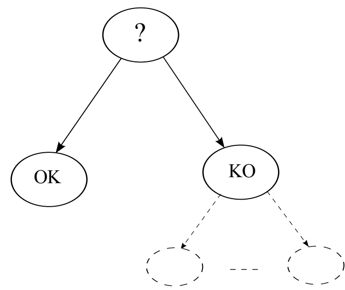

Figure 3: Abstract Representation

rhythm and *heart rate* to distinguish normal and abnormal heart. The specification consists of just three state variables ($inv1 - int3$) *Sinus*, *Heart_Rate* and *Heart_State*. *Sinus* variable is represented by *YesNoState* as an enumerated sets. Last two variables *Heart_Rate* and *Heart_State* are introduced as to show heart rate limit and heart states. One possible approach is to introduce a set of variables (*RR_Int_equidistant*, *PP_Int_equidistant*, *P_Positive*, *PP_Interval* and *RR_Interval*) representing total functions mapping leads (LEADS) to an standard data type ($BOOL$, $\mathbb{N}$) in invariants ($inv4 - inv8$). The RR and PP equidistant intervals in the ECG signal are represented by variables *RR_Int_equidistant* and *PP_Int_equidistant* as the total functions from *LEADS* to $BOOL$. *RR_Int_equidistant* and *PP_Int_equidistant* are functions which represent RR and PP equidistant intervals states in boolean form. A variable *P_Positive* represents positive wave of the signal also as a total function from *LEADS* to BOOL. The *P_Positive* function is used to show the positive visualization of the P-waves. The next variables PP and RR intervals in the ECG signal are represented by the variables *PP_Interval* and *RR_Interval* as total functions from *LEADS* to $\mathbb{N}$. *PP_Interval* and *RR_Interval* functions are used to calculate PP and RR-intervals.

$inv1: Sinus \in YesNoState$
$inv2: Heart\_Rate \in 1\,..\,300$
$inv3: Heart\_State \in HState$
$inv4: RR\_Int\_equidistant \in LEADS \rightarrow BOOL$
$inv5: PP\_Int\_equidistant \in LEADS \rightarrow BOOL$
$inv6: P\_Positive \in LEADS \rightarrow BOOL$
$inv7: PP\_Interval \in LEADS \rightarrow \mathbb{N}$
$inv8: RR\_Interval \in LEADS \rightarrow \mathbb{N}$
$inv9: P\_Positive(II) = FALSE \Rightarrow Sinus = No$
$inv10: ((\forall l \cdot l \in \{II, V1, V2\} \Rightarrow$
$\quad PP\_Int\_equidistant(l) = FALSE \vee$
$\quad RR\_Int\_equidistant(l) = FALSE \vee$
$\quad RR\_Interval(l) \neq PP\_Interval(l))$
$\quad \vee$
$\quad P\_Positive(II) = FALSE) \Rightarrow Sinus = No$
$inv11: Sinus = Yes \Rightarrow ((\exists l \cdot l \in \{II, V1, V2\} \wedge$
$\quad PP\_Int\_equidistant(l) = TRUE \wedge$
$\quad RR\_Int\_equidistant(l) = TRUE \wedge$
$\quad RR\_Interval(l) = PP\_Interval(l))$
$\quad \wedge$
$\quad P\_Positive(II) = TRUE)$
$inv12: Heart\_Rate \in 60\,..\,100 \wedge Sinus = Yes \Rightarrow$
$\quad Heart\_State = OK$
$inv13: Heart\_Rate \in 1\,..\,300 \setminus 60\,..\,100 \wedge Sinus = Yes$
$\quad \Rightarrow Heart\_State = KO$
$inv14: Heart\_Rate \in 60\,..\,100 \wedge Sinus = No \Rightarrow$
$\quad Heart\_State = KO$

All invariants ($inv9 - inv14$) represent safety properties and these are used to verify required conditions for the ECG interpretation protocol using all possible behavior of the heart system and analysis of signal features which are collected from the ECG signals. All these safety properties are designed under the supervision of cardiologist experts to verify the correctness of the formal model. These invariants in form of safety properties are extracted from the original protocol.

The invariant ($inv9$) states that if positive visualization of P-wave is $FALSE$, then there is no sinus rhythm. According to the clinical document, lead II is best for visualization of P-waves to determine the presence of sinus rhythm. Next invariant ($inv10$) is more stronger invariant to identify non existence of sinus rhythm. This invariant states that if PP intervals (*PP_Int_equidistant*) or RR intervals (*RR_Int_equidistant*) are not equidistant ($FALSE$), or RR intervals (*RR_Interval*) and PP intervals (*PP_Interval*) are not equivalent, in all leads (II,V1,V2), or positive visualization of P-wave in lead II is $FALSE$, then there is no sinus rhythm. Similarly, next invariant ($inv11$) confirms, if the rhythm is sinus, then the PP intervals (*PP_Int_equidistant*) and RR intervals (*RR_Int_equidistant*) are equidistant, and RR intervals (*RR_Interval*) and PP intervals (*PP_Interval*) are equal, exist in any leads (II,V1,V2), and the P-wave is positive in lead II. The invariant ($inv12$) represents that if heart rate (*Heart_Rate*) is belonging between 60-100 bpm and sinus rhythm is Yes, then *Heart_State* is OK. Next two invariants ($inv13 - inv14$) represent KO state of Heart, mean heart has any disease. The invariant ($inv13$) states that if heart rate (*Heart_Rate*) is belonging between less than 60 bpm and greater than 100 bpm but less then 300 bpm, and sinus rhythm is Yes, then heart state (*Heart_State*) is KO. Similarly, in last invariant ($inv14$) represents that if heart rate (*Heart_Rate*) is in between 60-100 bpm and sinus rhythm is No, then *Heart_State* is KO, means heart has any disease.

Three significant events *Rhythm_test_TRUE*, *Rhythm_test_FALSE* and *Rhythm_test_TRUE_abRate* are introduced in the abstract model. The *Rhythm_test_TRUE* represents successful ECG testing and found sinus rhythm *Yes* and heart state is OK . The next event *Rhythm_test_FALSE* represents successful ECG testing and found sinus rhythm is *No* and heart state is *KO*. Third event *Rhythm_test_TRUE_abRate* represents successful ECG testing and found sinus rhythm is *Yes* and heart state is *KO* due to abnormal heart rate. These events are the abstract events, which are equivalent to the first step of diagnosis of the ECG signal of the original protocol. We have taken some assumptions for modeling the medical protocol. These assumptions are extracted from the original protocol. In our formal model all invariants and assumptions are verified with the medical experts. Our developed formal are always compile with existing original protocols.

Mostly events are used to test criteria of possible disease using ECG features. The criteria for testing sinus rhythm is to focus on leads V1, V2, and II. Leads V1 and II are best for visualization of P-waves to determine the presence of sinus rhythm or an arrhythmia, and V1 and V2 are best to observe for bundle branch block. If P-waves are not clearly visible in V1, assess them in lead II, which usually shows well-formed P-waves [37]. Identification of the P-wave and then the RR intervals allows the interpreter to discover immediately whether the rhythm is sinus or other and to take the following steps:

- Confirm, if the rhythm is sinus, that the RR intervals are equidistant, that the P-wave is positive in lead II, and that the PP intervals are equidistant and equal to the RR interval.
- Do an arrhythmia assessment if the rhythm is abnormal.
- Determine the heart rate.

EVENT Rhythm_test_TRUE
  ANY $rate$
  WHEN
    grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$
    $RR\_Int\_equidistant(l) = TRUE \wedge$
    $RR\_Interval(l) = PP\_Interval(l)) \wedge$
    $P\_Positive(II) = TRUE$
    grd2 : $rate \in 60 \,..\, 100$
  THEN
    act1 : $Sinus := Yes$
    act2 : $Heart\_Rate := rate$
    act3 : $Heart\_State := OK$
END

EVENT **Rhythm_test_FALSE**
ANY $rate$
WHEN
grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE$
$\lor RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l)) \lor$
$P\_Positive(II) = FALSE$
grd2 : $rate \in 1 \,..\, 300$
THEN
act1 : $Sinus := No$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := KO$
END

EVENT **Rhythm_test_TRUE_abRate**
ANY $rate$
WHEN
grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l)) \land$
$P\_Positive(II) = TRUE$
grd2 : $rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$
THEN
act1 : $Sinus := Yes$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := KO$
END

In the abstract model, we have seen that sinus rhythm and heart rate are introduced for the ECG interpretation in a single atomic step. This provides for a clear and simple specification of the essence of the basic ECG interpretation protocol and predicts the heart state (OK or KO). However, in the real protocol, the ECG interpretation and heart state prediction is not atomic. Instead, the ECG interpretation and prediction are also encounter lots of diagnosis to find the various kinds of heart diseases.

6.2. Overview of the Full Refinement Chain

So far we have described our abstract model of the ECG interpretation protocol. Every level of refinement introduces new context file for adding static properties of the system and list of heart diseases after introducing certain protocol of the ECG interpretation. Every refinement level is used to introduce new set of diagnosis criteria to test the ECG signals. Rather than presenting the other chain of refinement stages in similar detail (see in section 6.1), we will just present a sufficient overview of the remaining refinement stages helping the reader to understand the rational of each refinement stage for formalising the ECG interpretation protocol.

6.2.1. First Refinement : Assess intervals and blocks

In an abnormal ECG signal, all ECG features are varying according to symptoms of the heart diseases. We will formalise the ECG interpretation protocol using incremental approach, where we determine all features of the ECG signal. This level of refinement determines the PR- and QRS-intervals for the ECG interpretation. These intervals classify different kinds of heart disease.

Invariants ($inv1 - inv3$) represent a set of new introduced variables in the refinement for expressing formalisation of the ECG interpretation protocol. These variables are *PR_Int*, *Disease_step2*, *QRS_Int*. Other variables (*M_Shape_Complex*, *Slurred_S*, *Notched_R*, *Small_R_QS* and *Slurred_S_duration*) are introduced as total functions in invariants ($inv4 - inv8$) where total functions are mapping from leads (LEADS) to $BOOL$ and $\mathbb{N}_1$, respectively. Function *M_Shape_Complex* returns existence of M-shape complex from the ECG signals in form of $TRUE$ and $FALSE$. The function *Slurred_S* represents Slurred S-wave, the function *Notched_R* represents notched R-wave and the function *Small_R_QS* represents small R or QS waves, in boolean form. The function *Slurred_S_duration* is used to calculate slurred S duration. A set of invariants ($inv9 - inv14$) represent safety properties to validate formal representation of the ECG interpretation protocol. All these properties are derived from the original protocol to verify the correctness and consistency of the system. These properties are formulated through logic experts as well as cardiologist experts according to the original protocols. The main advantage of this technique is that if any property is not holdoing by the model, then it helps to find anomalies or to find missing parts of the model such as required conditions and parameters.

Invariants ($inv9 - inv13$) represent an abnormal state of heart (KO) due to finding any disease and unsatisfiable condition for features of the ECG signal, in formal diagnosis process. While the last invariant ($inv14$) represents all required properties for a normal heart. It states that if heart rate is in between 60 to 100 bpm, sinus rhythm is Yes, PR interval is less than or equal to 200 ms and QRS interval is less then 120 ms, then the heart state is OK.

$$
\begin{array}{l}
inv1 : PR\_Int \in 120 \,..\, 250 \\
inv2 : Disease\_step2 \in Disease\_Codes\_Step2 \\
inv3 : QRS\_Int \in 50 \,..\, 150 \\
inv4 : M\_Shape\_Complex \in LEADS \rightarrow BOOL \\
inv5 : Slurred\_S \in LEADS \rightarrow BOOL \\
inv6 : Notched\_R \in LEADS \rightarrow BOOL \\
inv7 : Small\_R\_QS \in LEADS \rightarrow BOOL \\
inv8 : Slurred\_S\_duration \in LEADS \rightarrow \mathbb{N}_1 \\
inv9 : Sinus = Yes \wedge PR\_Int > 200 \wedge Disease\_step2 = \\
\qquad First\_degree\_AV\_Block \Rightarrow Heart\_State = KO \\
inv10 : Sinus = Yes \wedge QRS\_Int \geq 120 \wedge \\
\qquad Disease\_step2 \in \{LBBB, RBBB\} \Rightarrow Heart\_State = KO \\
inv11 : Sinus = Yes \wedge Disease\_step2 = First\_degree\_AV\_Block \\
\qquad \Rightarrow Heart\_State = KO \\
inv12 : Sinus = Yes \wedge Disease\_step2 = LBBB \Rightarrow \\
\qquad Heart\_State = KO \\
inv13 : Sinus = Yes \wedge Disease\_step2 = RBBB \Rightarrow \\
\qquad Heart\_State = KO \\
inv14 : Heart\_Rate \in 60 \,..\, 100 \wedge Sinus = Yes \wedge PR\_Int \leq 200 \\
\qquad \wedge QRS\_Int < 120 \Rightarrow Heart\_State = OK
\end{array}
$$

To express formal logic for a new set of diagnoses for the ECG signal, we have introduced three events *PR_test*, *QRS_Test_LBBB* and *QRS_Test_RBBB*. The *PR_Test* intervals represent, if PR intervals are abnormal (>200 ms), consider first-degree atrioventricular (AV) block. The next two events *QRS_Test_LBBB* and *QRS_Test_RBBB* are used to assess the QRS duration for bundle branch block and states that, if QRS interval is ≥120 ms, bundle branch block is present.

Understanding the genesis of the QRS complex is an essential step and clarifies the ECG manifestations of bundle branch blocks [37]. We have formalised the basic criteria to distinguish between RBBB and LBBB in diagnosis process. The basic description of RBBB and LBBB are given as follows:

Right Bundle Branch Block (RBBB)

- QRS duration $\geq$120 ms.
- M-shaped complex in V1 and V2.
- Slurred S-wave in leads 1, V5, V6; and an S-wave that is of greater amplitude (length) than the preceding R-wave.

Left Bundle Branch Block (LBBB)

- QRS duration $\geq$120 ms.
- A small R- or QS-wave in V1 and V2.
- A notched R-wave in leads 1, V5, and V6.

Due to limited space, we will not show the formal representation of introduced events. For complete detail see [45].

6.2.2. Second Refinement : Assess for nonspecific intraventricular conduction delay and wolff-parkinson-white syndrome

This level of refinement of the ECG interpretation assess for nonspecific intraventricular conduction delay (IVCD) and wolff-parkinson-white (WPW) syndrome. WPW syndrome may mimic an inferior MI (see in further refinements). If WPW syndrome, RBBB, or LBBB is not present, interpret as nonspecific intraventricular conduction delay (IVCD) and assess for the presence of electronic pacing [37]. Some new variables (*Delta_Wave* and *Disease_step3*) are introduced in this refinement to assess atypical right bundle branch block using ECG signal. Two invariants ($inv3 - inv4$) are used to declare new variables in form of the total function mapping leads (LEADS) to $BOOL$. These functions are used to calculate ST-segment elevation and epsilon wave, respectively. Invariants ($inv5 - inv8$) represent an abnormal state of heart (KO) when sinus rhythm is Yes and any new particular disease is found in this refinement. All these properties are derived from the original protocol to verify the correctness and consistency of the system according to the cardiologist.

$$
\begin{array}{l}
inv1 : Delta\_Wave \in \mathbb{N} \\
inv2 : Disease\_step3 \in Disease\_Codes\_Step3 \\
inv3 : ST\_elevation \in LEADS \rightarrow BOOL \\
inv4 : Epsilon\_Wave \in LEADS \rightarrow BOOL \\
inv5 : Sinus = Yes \wedge Disease\_step3 = WPW\_Syndrome \Rightarrow \\
\quad\quad Heart\_State = KO \\
inv6 : Sinus = Yes \wedge Disease\_step3 = Brugada\_Syndrome \Rightarrow \\
\quad\quad Heart\_State = KO \\
inv7 : Sinus = Yes \wedge Disease\_step3 = RV\_Dysplasia \Rightarrow \\
\quad\quad Heart\_State = KO \\
inv8 : Sinus = Yes \wedge Disease\_step3 = IVCD \Rightarrow \\
\quad\quad Heart\_State = KO
\end{array}
$$

We have introduced four events *QRS_Test_Atypical_RLBBB_WPW_Syndrome*, *QRS_Test_At-ypical_RBBB_Brugada_Syndrome*, *QRS_Test_Atypical_RBBB_RV-_Dysplasia* and *QRS_Test_Atypical_RBBB_IVCD* to interpret atypical right bundle branch block using QRS interval. The following criteria to assess are as follows:

- If the QRS duration is prolonged ≥110 ms and bundle branch block appears to be present but is atypical, consider WPW syndrome, particularly if there is a tall R wave in leads V1 and V2.
- Assess for a short PR interval ≤120 ms and for a delta wave.

6.2.3. Third Refinement : Assess for ST-segment elevation or depression

This refinement provides the criteria for ST-segments assessment by introducing some new variables (*ST_seg_ele* and *ST_depression*) in form of total function mapping leads (LEADS) to $\mathbb{N}$ in invariants ($inv2 - inv3$). ST-segment for elevation and ST depression features are calculated by *ST_seg_ele* and *ST_depression* functions. Invariants ($inv4 - inv8$) are introduced as representing the safety properties to confirm an abnormal state of heart (KO) when sinus rhythm is Yes and a new disease is found in this refinement.

$$
\begin{array}{ll}
inv1: & Disease\_step4 \in Disease\_Codes\_Step4 \\
inv2: & ST\_seg\_ele \in LEADS \rightarrow \mathbb{N} \\
inv3: & ST\_depression \in LEADS \rightarrow \mathbb{N} \\
inv4: & Sinus = Yes \land Disease\_step4 \in \\
 & \{Acute\_inferior\_MI, Acute\_anterior\_MI\} \\
 & \Rightarrow Heart\_State = KO \\
inv5: & Sinus = Yes \land Disease\_step4 = STEMI \Rightarrow \\
 & Heart\_State = KO \\
inv6: & Sinus = Yes \land Disease\_step4 \in \{Troponin, CK\_MB\} \Rightarrow \\
 & Heart\_State = KO \\
inv7: & Sinus = Yes \land Disease\_step4 = Non\_STEMI \Rightarrow \\
 & Heart\_State = KO \\
inv8: & Sinus = Yes \land Disease\_step4 = Ischemia \Rightarrow \\
 & Heart\_State = KO
\end{array}
$$

Four new events *ST_seg_elevation_YES*, *ST_seg_elevation_NOTCKMB_Yes*, *ST_seg_elevation_-NO_TCKMB_No* and *Acute_IA_MI* are defined to cover *diagnosis* related to the ECG signals. All these events are used to interpret about the ECG signal using ST-segment elevation or depression features [37]. To assess the ST-segments elevation or depression, we have formalised the following textual criteria:

- Focus on the ST-segment for elevation or depression. ST-elevation ≥1000 μm (0.1 mV) in two or more contiguous ECG leads in a patient with chest pain indicates ST elevation MI (STEMI). The diagnosis is strengthened if there is reciprocal depression.
- ST-elevation in leads II, III, and aVF, with marked reciprocal depression in leads I and aVL, diagnostic of acute inferior MI.

- ST-segment elevation in V1 through V5, caused by extensive acute anterior MI.
- The ECG of a patient with a subtotal occlusion of the left main coronary artery. Note the ST elevation in aVR is greater than the ST elevation in V1, a recently identified marker of left main coronary disease.
- Features of non-ST-elevation MI (nonQ-wave MI).
- Elevation of the ST-segment may occur as a normal variant and ST-segment abnormalities and MI.

These textual sentences are formulated in incremental development of our ECG protocol. This refinement advises scrutiny of the ST-segment before assessment of T-waves, electrical axis, QT interval, and hypertrophy because the diagnosis of acute MI or ischemia is vital and depends on careful assessment of the ST-segment. Above given criteria are more complex and too ambiguous to represent. Therefore, we have formalised this part through careful cross reading of many reliable sources such as literature and encounter suggestion of the medical experts.

6.2.4. Fourth Refinement : Assess for pathologic Q-wave

This refinement only introduces new guidelines to interpret Q-wave feature of the ECG signal and assessment related diseases to the Q-wave and R-wave [37]. Some new variables are represented by set of invariants ($inv1-inv2$) to handle the required features of Q-wave and R-wave to diagnose the ECG signal. The functions *Q_Normal_Status* and *R_Normal_Status* represent normal state of Q and R-waves in boolean form. Next three invariants ($inv3-inv5$) are used to declare new variables in form of total function mapping leads (LEADS) to $\mathbb{N}$, and invariant ($inv6$) is also total function mapping leads (LEAD) to $BOOL$. The functions *Q_Width*, *Q_Depth* and *R_Depth* calculate Q-wave width, Q-wave depth and R-wave depth, respectively.The last function *Q_Wave_State* represents boolean state of Q-wave for all leads. Two other new variables *Age_of_Inf* and *Mice_State* represent infarction age and miscellaneous states. An enumerated set of infarction age and miscellaneous states define as $Age\_of\_Infarct = \{recent, indeterminate, old\}$ and $Mice\_State5 = \{Exclude\_Mimics\_MI, late\_transition, normal\_variant, borderline\_Qs, NMS\}$, respectively in context. The variable *Disease_step5* represents a group of diseases of this refinement level as analysis of Q-wave from the ECG signals. Invariants ($inv10-inv13$) are introduced as representing the safety properties to confirm an abnormal state of heart (KO). All invariants have similar form for checking heart state under various disease conditions. These invariants state that if sinus rhythm is Yes and new disease is found, then the heart must be in abnormal state (KO).

$inv1 : Q\_Normal\_Status \in BOOL$
$inv2 : R\_Normal\_Status \in BOOL$
$inv3 : Q\_Width \in LEADS \rightarrow \mathbb{N}$
$inv4 : Q\_Depth \in LEADS \rightarrow \mathbb{N}$
$inv5 : R\_Depth \in LEADS \rightarrow \mathbb{N}$
$inv6 : Q\_Wave\_State \in LEADS \rightarrow BOOL$
$inv7 : Age\_of\_Inf \in Age\_of\_Infarct$
$inv8 : Mice\_State \in Mice\_State5$
$inv9 : Disease\_step5 \in Disease\_Codes\_Step5$
$inv10 : Sinus = Yes \land Disease\_step4 = Acute\_anterior\_MI \Rightarrow Heart\_State = KO$
$inv11 : Sinus = Yes \land Disease\_step4 = Acute\_inferior\_MI \Rightarrow Heart\_State = KO$
$inv12 : Sinus = Yes \land Disease\_step5 = Hypertrophic\_cardiomyopathy \Rightarrow Heart\_State = KO$
$inv13 : Sinus = Yes \land Disease\_step5 \in \{anterior\_MI, LVH, emphysema, lateral\_MI\} \Rightarrow Heart\_State = KO$

In this level of refinement, we have introduced nine events (*Q_Assessment_Normal*, *Q_Assess-ment_Abnormal_AMI*, *Q_Assessment_Abnormal_IMI*, *Determine-_Age_of_Infarct*, *Exclude_Mimics*, *R_Assessment_Normal*, *R_Assessment_Abnormal*, *R_Q_Assessment_R_Abnormal_V1234* and *R_Q_Assessment_R_Abnormal-_V56*) for assessing the Q-wave and R-wave in all leads of the ECG signals. We have represented the formal notation of following guidelines, which are used to assess the Q-wave and the R-wave:

- Assess for the loss of R waves-pathologic Q-waves in leads I, II, III, aVL, and aVF.
- Assess for R wave progression in V2 through V4. The variation in the normal QRS configuration that occurs with rotation. The R wave amplitude should measure from 1 mm to at least 20000 μm in V3 and V4. Loss of R waves in V1 through V4 with ST-segment elevation indicates acute anterior MI.
- Loss of R wave in leads V1 through V3 with the ST-segment isoelectric and the T-wave inverted may be interpreted as anteroseptal MI age indeterminate (i.e., infarction in the recent or distant past). Features are given of old anterior MI and lateral infarction in this refinement.

Sometimes, R-wave progression in leads V2 through V4 are very poor, may be caused by the following reasons: improper lead placement, late transition, anteroseptal or anteroapical MI, LVH Severe chronic obstructive pulmonary disease, particularly emphysemaemphysema may cause QS complexes in leads V1 through V4, which may mimic MI; a repeat ECG with recording electrodes placed one intercostal space below the routine locations should cause R waves to be observed in leads V2 through V4, Hypertrophic cardiomyopathy, LBBB [37].

6.2.5. Fifth Refinement : P-wave

This refinement level introduces a criteria to assess the P-wave for abnormalities including atrial hypertrophy into the ECG signal [37]. A new variable *Disease_step6* is introduced in this refinement to introduce a set of diseases related to the P-wave. Some new variables are also introduced to assess the P-wave from 12-leads ECG signals, which are represented by $inv2 - inv4$. First two invariants introduce new variables in form of total function mapping from leads (LEADS) to $\mathbb{N}$. These functions return height and broadness of P-waves. Next invariant ($inv4$) represents total function mapping leads (LEADS) to $BOOL$. It returns diphasic state in the boolen form. Invariants ($inv5 - inv7$) are representing the confirmation of the abnormal state of heart (KO). These invariants state that if sinus rhythm is Yes and a new disease is found, then heart will be in abnormal state. In invariant ($inv5$) is checking for existence of multiple diseases during the P-wave diagnosis. Five new events *P_Wave_assessment_Peaked_Broad_No*, *P_Wave_assessment_Peaked_Yes*, *P_Wave_assessment_Peaked_Yes_Check_RAE*, *P_Wave_assessment_Broad_Yes* and *P_Wave_asses-sment_Broad_Yes_Check_LAE* are introduced to assess the P-wave.

$$
\begin{array}{l}
inv1 : Disease\_step6 \in Disease\_Codes\_Step6 \\
inv2 : P\_Wave\_Peak \in LEADS \to \mathbb{N} \\
inv3 : P\_Wave\_Broad \in LEADS \to \mathbb{N} \\
inv4 : Diphasic \in LEADS \to BOOL \\
inv5 : Sinus = Yes \wedge Disease\_step6 \in \\
\quad \{RVH, RV\_strain, pulmonary\_embolism, \\
\quad RAE, mitral\_stenosis, mitral\_regurgitation, LV\_failure, \\
\quad LAE, dilated\_cardiomyopathy, LVH\_cause\} \\
\quad \Rightarrow Heart\_State = KO \\
inv6 : Sinus = Yes \wedge Disease\_step6 = LAE \Rightarrow Heart\_State = KO \\
inv7 : Sinus = Yes \wedge Disease\_step6 = RAE \Rightarrow Heart\_State = KO
\end{array}
$$

The textual representation of formal notation of the P-wave assessment is given in [37]. We have formalised all textual guidelines.

6.2.6. Sixth Refinement : Assess for left and right ventricular hypertrophy

Left Ventricular Hypertrophy (LVH) and Right Ventricular Hypertrophy (RVH) are assessed by this refinement. The criteria for LVH and RVH are not applicable if bundle branch block is present [37]. Thus, it is essential to exclude LBBB and RBBB early in the interpretive sequences as delineated previously in refinement 2 and refinement 3. This refinement introduces two new variables *S_Depth* and *R_S_Ratio* in form of total function mapping leads (LEADS) to $\mathbb{N}$. These functions are used to calculate S-wave depth and ratio of R-wave and S-wave from 12-leads ECG signal. Invariants ($inv3 - inv4$) are used to verify an abnormal state (KO) of the heart in case of detecting any disease. Two new events (*LVH_Assessment* and *RVH_Assessment*) are introduced to assess LVH and RVH from 12-leads ECG. Detailed textual representation of assessment of LVH and RVH is given in [37].

$$
\begin{array}{l}
inv1 : S\_Depth \in LEADS \to \mathbb{N} \\
inv2 : R\_S\_Ratio \in LEADS \to \mathbb{N} \\
inv3 : Sinus = Yes \wedge Disease\_step6 = RVH \Rightarrow \\
\quad Heart\_State = KO \\
inv4 : Sinus = Yes \wedge Disease\_step6 = LVH\_cause \Rightarrow \\
\quad Heart\_State = KO
\end{array}
$$

6.2.7. Seventh Refinement : Assess T-wave

This refinement is used to assess the pattern of T-wave changes in 12-leads ECG signals. T-wave changes are usually nonspecific [37]. The T-wave inversion associated with ST-segment depression or elevation indicates myocardial ischemia. A new variable *T_Normal_Status* represents as a boolean state like $TRUE$ is for normal state, and $FALSE$ is for abnormal state. Variable *Disease_step8* is introduced in this refinement to assess a set of diseases related to T-wave from the ECG signals. Invariants ($inv3 - inv8$) represent variables in form of total function mapping leads (LEADS) to possible other attributes (*T_State*,*T_State_B* , $BOOL$, $\mathbb{N}$ and *T_State_l_d*). The function *T_Wave_State* represents T-wave states like peaked or flat, or inverted. Similarly, the function *T_Wave_State_B* also represents the T-wave states like upright or inverted, or variable using second method of diagnosis of the T-wave. The function *Abnormal_Shaped_ST* and *Asy_T_Inversion_strain* returns boolean state of the abnormal ST-shape and asymmetric T-wave inversion strain pattern, respectively. Function *T_inversion* calculates deep T-wave inversion and last function *T_inversion_l_d* represents localized and diffuse T-inversion.

$$
\begin{array}{l}
inv1 : T\_Normal\_Status \in BOOL \\
inv2 : Disease\_step8 \in Disease\_Codes\_Step8 \\
inv3 : T\_Wave\_State \in LEADS \rightarrow T\_State \\
inv4 : T\_Wave\_State\_B \in LEADS \rightarrow T\_State\_B \\
inv5 : Abnormal\_Shaped\_ST \in LEADS \rightarrow BOOL \\
inv6 : Asy\_T\_Inversion\_strain \in LEADS \rightarrow BOOL \\
inv7 : T\_inversion \in LEADS \rightarrow \mathbb{N} \\
inv8 : T\_inversion\_l\_d \in LEADS \rightarrow T\_State\_l\_d \\
inv9 : Sinus = Yes \wedge Disease\_step8 = Nonspecific \Rightarrow \\
\quad Heart\_State = KO \\
inv10 : Sinus = Yes \wedge Disease\_step8 = \\
\quad Nonspecific\_ST\_T\_changes \\
\quad \Rightarrow Heart\_State = KO \\
inv11 : Sinus = Yes \wedge Disease\_step8 = posterior\_MI \Rightarrow \\
\quad Heart\_State = KO \\
inv12 : Sinus = Yes \wedge Disease\_step8 \in \{Definite\_ischemia, \\
\quad Probable\_ischemia, Digitalis\_effect\} \Rightarrow \\
\quad Heart\_State = KO \\
inv13 : Sinus = Yes \wedge Disease\_step8 = Definite\_ischemia \Rightarrow \\
\quad Heart\_State = KO \\
inv14 : Sinus = Yes \wedge Disease\_step8 = Probable\_ischemia \Rightarrow \\
\quad Heart\_State = KO \\
inv15 : Sinus = Yes \wedge Disease\_step8\_B \in \\
\quad \{Cardiomyopathy, other\_nonspecific\} \\
\quad \Rightarrow Heart\_State = KO
\end{array}
$$

From $inv9$ to $inv15$ represent abnormal state of heart due to finding some diseases. All these invariants are similar to the previous level of refinements. This refinement is very complex and we have formalised two alternate diagnosis for the ECG signal. We have introduced many events to assess the T-wave from the ECG signals and predict various diseases related to the T-wave. Events are *T_Wave_Assessment_Peaked_V123456*, *T_Wave_Assessment_Peaked_V12*, *T_Wave_Assessment_Peaked_V12_MI*, *T_Wave_Assessment_Flat*, *T_Wave_Assessment_Inverted_Yes*, *T_Wave_Assessment_Inverted_No*, *T_Wave_Assessment_Inverted_Yes_PM*, *T_Wave_Assessment_B*, *T_Wave-_Assessment_B_DI*, *T_Inversion_Likely_Ischemia*, *T_Inversion_Diffuse_B*. All these events estimate the different kinds of properties from the T-wave signal for obtaining the correct heart disease. A long textual representation for analysing the T-wave is given in [37].

6.2.8. Eighth Refinement : Assess Electrical Axis

After finding all kinds of information about abnormal ECG, it is also essential to check the electrical axis (see Table 2) using two simple clues:

- If leads I and aVF are upright, the axis is normal.
- The axis is perpendicular to the lead with the most equiphasic or smallest QRS deflection. Left-axis deviation and the commonly associated left anterior fascicular block are visible in ECG signal.

Most equiphasic lead	Lead perpendicular	Axis
		Lead I and aVF positive = normal axis
III	aVR	Normal = +30 degrees
aVL	II	Normal = +60 degrees Lead I positive and aVF negative = Left axis
II	aVL (QRS positive)	Left = -30 degrees
aVR	III (QRS negative)	Left = -60 degrees
I	aVF (QRS negative)	Left = -90 degrees Lead I negative and aVF positive = right axis
aVR	III (QRS positive)	Right = +120 degrees
II	aVL (QRS negative)	Right = +150 degrees

Table 2: Electrical Axis

This refinement is very essential refinement for the ECG interpretation because of the different angle of the ECG signal gives different output and angle based prediction can be changed [37]. So, for accuracy of the ECG interpretation electrical axis must be included. New variables *minAngle*, *maxAngle*, *Axis_Devi* and *Disease_step9* have been defined here for assessment of the electrical axis. A new variable *QRS_Axis_State* is defined as total function mapping from leads (LEADS) to *QRS_directions*. This function represents QRS-axis direction of the leads. Two invariants ($inv6 - inv7$) represent safety properties in assessment of the correct axis. These invariants are verifying an abnormal state of heart (KO) using axis position.

$$
\begin{array}{l}
inv1 : minAngle \in -90\,..\,180 \\
inv2 : maxAngle \in -90\,..\,180 \\
inv3 : Axis\_Devi \in Axis\_deviation \\
inv4 : Disease\_step9 \in Disease\_Codes\_Step9 \\
inv5 : QRS\_Axis\_State \in LEADS \rightarrow QRS\_directions \\
inv6 : Disease\_step9 \in \{LPFB, Dextrocardia, NV\_MSEC\} \land \\
\qquad maxAngle = 180 \land minAngle = 110 \Rightarrow Heart\_State = KO \\
inv7 : Disease\_step9 \in \{LAFB, MSCHD, Some\_Form\_VT, ED\_OC\} \\
\qquad \land maxAngle = -90 \land minAngle = -30 \Rightarrow Heart\_State = KO
\end{array}
$$

In this refinement level, we introduce various events for assessing different kinds of features from 12 leads ECG signal corresponding to the angle. Following events are introduced in this refinement: *Axis_Assessment_QRS_upright_Yes_Age_less_40*, *Axis_Assessment_QRS_upright_Yes_-Age_gre_40*, *Axis_Assessment_QRS_upright_No_QRS_positive*, *Axis_Assessment_QRS_upright_No-_QRS_negative*, *Misc_Disease_Step9_LAD*, *Misc_Disease_Step9_RAD*, *R_Q_Assessment_R_Abno-rmal_V56_axis_deviation*.

6.2.9. Ninth Refinement : Assess for miscellaneous conditions

There are lots of heart diseases and it is very difficult to predict everything. A lot of conditions make it more and more ambiguous. This refinement level keeps multiple miscellaneous conditions about the ECG interpretation [37]. Following conditions are given for miscellaneous conditions as follows:

- Artificial pacemakers: If electronic pacing is confirmed, usually no other diagnosis can be made from the ECG.
- Prolonged QT syndrome: See normal QT parameters listed in Table 3. No complicated formula is required for assessment of the QT intervals.

Heart rate (bpm)	Male	Female
45−65	<470	<480
66−100	<410	<430
>100	<360	<370

Table 3: Clinically useful approximation of upper limit of QT interval (ms.)

A variable *MC_Step10_Test_Needed* is declared to represent miscellaneous condition test as a boolean type $TRUE$ or $FALSE$. Variable *Disease_step10* is introduced in this refinement to assess a set of diseases of miscellaneous conditions from the ECG signal. Next two invariants ($inv2 - inv3$) represent the abnormality of the heart state (KO) in case of discovery of new miscellaneous diseases. In this refinement, we introduce only two events (*Miscellaneous_Conditions_Step10* and *Misc_Disease_Step10_Dextrcardia_Test*) to discover miscellaneous conditions from the ECG signal.

$$
\begin{array}{l}
inv1 : MC\_Step10\_Test\_Needed \in BOOL \\
inv2 : Disease\_step10 \in Misc_Disease\_Codes\_Step10 \\
inv3 : Sinus = Yes \land Disease\_step10 \in \{Incomplete\_RBBB, \\
\quad Long\_QT, Hypokalemia, Digitalis\_toxicity, Hypothermia, \\
\quad Electronic\_pacing, Pericarditis, , Hypercalcemia\} \\
\quad Electrical\_alternans \Rightarrow Heart\_State = KO \\
inv4 : Sinus = Yes \land Disease\_step9 = Dextrocardia \Rightarrow \\
\quad Heart\_State = KO
\end{array}
$$

6.2.10. Tenth Refinement : Assess Arrhythmias

This is the final refinement of the ECG interpretation of the system. In this refinement, we introduce different kinds of tachyarrhythmias and give the protocols for assessment as follows:

- Narrow complex tachycardia: Gives the differential diagnosis of narrow QRS complex tachycardia.

- Wide complex tachycardia: Gives the differential diagnosis of wide QRS complex tachycardia.

A new variable *NW_QRS_Tachycardia_RT_State* is defined to express QRS tachicardia regular or irregular state using $inv1$. Variable *Disease_step11* is introduced in this refinement to assess arrhythmias from the ECG signals. All rest of the invariants ($inv3 - inv9$) represent abnormal state (KO) of the heart after analysing arrhythmia and related disease. All invariants have similar kinds of properties. We introduce five new events to assess tachyarrhythmias from the 12-leads ECG signals in case of abnormal rhythm. Five events are *Rhythm_test_FALSE_Step11*, *Step11_N_QRS_Tachycardia_Regular*, *Step11_N_QRS_Tachycardia_Irregular*, *Step11_W_QRS_Tachycardia_Regular* and *Step11_W_QRS_Tachycardia_Irregular*.

$inv1: NW\_QRS\_Tachycardia\_RT\_State \in NW\_QRS\_Tachycardia\_RI$
$inv2: Disease\_step11 \in Misc\_Disease\_Codes\_Step11$
$inv3: Sinus = Yes \land Disease\_step11 \in \{Ventricular\_Premature\_Beats, Nodal\_Premature\_Beats, Bradyarrhythmias, Narrow\_QRS\_Tachycardias, Wide\_QRS\_Tachycardias, Atrial\_Premature\_Beats\} \Rightarrow Heart\_State = KO$

$inv4: Sinus = Yes \land Distease\_step11\_NW\_QRST \in \{Sinus\_Tachycardia, Supraventricular\_Tachycardia, WPW\_Syndrome\_Orthodromic, Torsades\_de\_pointes, Atrial\_Tachycardia, AF\_Fixed\_AV\_Conduction, AVNRT, Ventricular\_Tachycardia, WPW\_Syndrome\_Antidromic, AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti, AF\_BBB\_WPW\_Synd\_Antidromic\} \Rightarrow Heart\_State = KO$

$inv5: Sinus = Yes \land Distease\_step11\_NW\_QRST \in \{AF\_Variable\_AV\_Conduction, AVNRT, AT\_Paroxysmal\_NParoxysmal, AT\_Variable\_AV\_Block, AF\_Fixed\_AV\_Conduction, WPW\_Syndrome\_OCMT, Sinus\_Tachycardia, Multifocal\_Atrial\_Tachycardia, Atrail\_Fibrillation\} \Rightarrow Heart\_State = KO$

$inv6: NW\_QRS\_Tachycardia\_RT\_State = Regular \land Distease\_step11\_NW\_QRST \in \{Sinus\_Tachycardia, WPW\_Syndrome\_OCMT, AF\_Fixed\_AV\_Conduction, AVNRT, AT\_Paroxysmal\_NParoxysmal\} \Rightarrow Heart\_State = KO$

$inv7: NW\_QRS\_Tachycardia\_RT\_State = Irregular \land Distease\_step11\_NW\_QRST \in \{Atrail\_Fibrillation, AT\_Variable\_AV\_Block, AF\_Variable\_AV\_Conduction, Multifocal\_Atrial\_Tachycardia\} \Rightarrow Heart\_State = KO$

$inv8: NW\_QRS\_Tachycardia\_RT\_State = Regular \land Distease\_step11\_NW\_QRST \in \{Ventricular\_Tachycardia, Sinus\_Tachycardia, AF\_Fixed\_AV\_Conduction, Supraventricular\_Tachycardia, Atrial\_Tachycardia, AVNRT, WPW\_Syndrome\_Antidromic, WPW\_Syndrome\_Orthodromic\} \Rightarrow Heart\_State = KO$

$inv9: NW\_QRS\_Tachycardia\_RT\_State = Irregular \land Distease\_step11\_NW\_QRST \in \{AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti, Torsades\_de\_pointes, AF\_BBB\_WPW\_Synd\_Antidromic\} \Rightarrow Heart\_State = KO$

In this report we have given only required safety properties in form invariants in all refinements. All these properties are derived from the original protocol to verify the correctness and consistency of the system. These properties are formulated through logic experts as well as cardiologist experts according to the original protocols. The main advantage of this technique is that if any property is not holdoing by the model, then it helps to find anomalies or to find missing parts of the model such as required conditions and parameters.

We have described here only summary informations about each refinement in form of basic description and required invariants of the ECG interpretation protocol using incremental refinement-based approach and omit detailed formalisation of events and proof details. To find complete formal representation of the ECG interpretation protocol see [45].

7. Statistical Analysis and lesson learned

7.1. Statistical Analysis

All the proof obligations for all ten refinements are generated and proved using the RODIN prover [5]. The Table 4 shows statistics of the ECG interpretation protocol using refinement approach. In the table, the POs column represents the total number of proof obligations generated for each level. The interactive POs column represents the number of those proof obligations that have to be proved interactively. Those proof obligations that are not proved interactively are proved completely automatically by the prover. The complete development of the ECG interpretation protocol system results in 599 (100%) proof obligations, in which 343 (58%) are proved automatically by the RODIN tool. The remaining 256 (42%) proof obligations are proved interactively using RODIN tool. So, all the proofs are discharged completely automatic as well as interactive for all refinement levels. All these proofs are involved either by the complexity of the formal expression that proved by *do case* or finiteness constraints on a set of leads. The main interactive steps involved instantiating for total function of different feature of the ECG interpretation in every level of refinement. In order to guarantee the correctness of the system, we have established various invariants in stepwise refinement. All these invariants are derived from the original protocol to verify the correctness and consistency of the system under the guidance of the cardiologist expert. Most of the invariants are introduced for checking the abnormality of the features of the ECG signal. Detection of abnormal criteria, the heart shows surety of the particular disease or a set of diseases. A set of diseases are distinguished in next level of refinements.

Model	Total number of POs	Automatic Proof	Interactive Proof
Abstract Model	41	33(80%)	8(20%)
First Refinement	61	54(88%)	7(12%)
Second Refinement	41	38(92%)	3(8%)
Third Refinement	51	36(70%)	15(30%)
Fourth Refinement	60	35(58%)	25(42%)
Fifth Refinement	43	22(51%)	21(49%)
Sixth Refinement	38	14(36%)	24(64%)
Seventh Refinement	124	29(23%)	95(77%)
Eighth Refinement	52	30(57%)	22(43%)
Ninth Refinement	21	9(42%)	12(52%)
Tenth Refinement	67	43(64%)	24(36%)
Total	599	343(58%)	256(42%)

Table 4: Proof statistics

7.2. Lesson learned

The task of modelling of the ECG interpretation protocol in Event B has required a significant effort. It is a typical knowledge engineering task, where the knowledge is the original document, is transformed into the Event B formal notation, which provides a significant hierarchical structure for analysing the ECG interpretation protocol and diagnose different kinds of heart diseases. As result, the Event B ECG interpretation protocol specification is much more lengthy than the original text: the original ECG interpretation protocol. The complete formal specification of the ECG interpretation protocol in Event B is more than 200 pages.

We consider that logic-based modeling approach is very difficult to model a complex medical protocol. This approach has required a good understanding of logic as well as knowledge medical protocol. We have spend a lot of time with medical experts to understand the structure of the medical protocols for formalising purpose. For modelling the ECG protocol, we have consulted with cardiologist and medical experts. The formal model of ECG protocol is based on original protocol and checked by medical experts.

We cannot strictly say that the formal representation of the ECG interpretation protocol in Event B modeling language has contributed to the improvement of the original protocol. Most important contribution is refinements-based formal development of the ECG interpretation protocol and generate a new optimal way of the ECG interpretation protocol for diagnosing the ECG signal. The developed formal model is proved and verifying according to the given protocol properties as discussed in formal development. Furthermore, the Event B formalisation has served to disambiguate unclarities in original document that resulted from the modelling stage: a number of ambiguity and repetition diagnosis problems with original document are uncovered and resolved by refining the formal specification of the ECG interpretation protocol in Event B. The formal model can help to restructure the original document of guidelines and protocols.

The verification attempts have served to clarify any remaining problems in the original ECG interpretation protocol document. More importantly, we have shown that it is possible in practice to systematically analyse whether a protocol formalised in Event B complies with certain medically relevant properties. Various properties of the ECG interpretation protocol have been the object of formal verification using the Event B system, with different type of results. Mostly the given properties of the ECG interpretation protocol have been confirmed by the formal representation of the ECG interpretation protocol. However, in other cases verification is not simple and lots of ambiguous informations, i.e. it is not possible to complete the proof or further development of model due to ambiguity. We have introduced some additional assumptions with the help of cardiologist experts for describing the conditions needed to make the property true and added more conditions to remove the ambiguity. These assumptions are missing piece of information in medical protocol, which helps to improve the medical protocol. We have applied a pragmatic approach to collect lots of informations through literature survey and medical experts's advises for finding the exact facts to introduce new assumptions and conditions for discharging all generated proof obligations.

For example, pieces of informations missing from the original ECG interpretation protocol like it is not given that how many leads should hold particular property during diagnosis. As per our solution we have applied test for particular properties in all leads. This results in a characterization of the circumstances under which the property holds. The obtained characterization is analyzed by medical experts under all possible conditions and it can be used either to redefine the property or to improve the original ECG interpretation protocol text by documenting the cases under which the property does (or does not) hold.

More importantly, numerous anomalies became apparent during the EVENT B modelling of the ECG interpretation protocol. Here we have used term anomaly to refer to any issue that are not able to represent satisfactory of the original ECG interpretation protocol. Some set of anomalies, which have found during the development of the system are described below. We have grouped all anomalies in three well known general categories: ambiguity, inconsistency and incompleteness.

7.2.1. Ambiguous

Ambiguous is well-known anomaly in area of formal representation and it is very hard to interpret. For instance, a problem we encountered while modelling the ECG interpretation protocol is determining whether the terms "ST-depression" and "ST-elevation" had the same meaning or not. These are terms that are used in the ECG interpretation original protocol, but not defined elsewhere. Similarly what is the difference between "ischemia", "Definite ischemia", "probable ischemia" and "likely ischemia".

In the ECG interpretation, there are 12 leads ECG signals, which are used for interpretation, but a lot of places in the original document not clarify in which lead the particular property should hold. Such kinds of informations are very ambiguous and give lots of confusions to model the system.

7.2.2. Inconsistencies

Inconsistencies are another kinds of anomalies which are always give conflicting results or different decisions on same patient data. The problems derived from inconsistent elements are very serious and as such must be avoided during development. The ECG interpretation protocol presents several inconsistencies. For instance, we found an inconsistency in form of applicable conditions in the ECG protocol. It expresses that the conditions are applicable for both "male" and "female" under some certain circumstances. However, elsewhere in the protocol an action is advised that these conditions of the protocol are not applicable for "female".

7.2.3. Incompleteness

Either missing pieces of information or insufficient information in original document are always related to the incompleteness anomaly. In either case, incompleteness hinders a correct interpretation of guidelines and protocols. For example, the original protocol contains “normal variant” factors to be considered when assessing T-wave. However, what normal variant exactly means is missing in the protocol. As an example of insufficient information for “normal variant”, we provide the class of disease for further analysis the system.

8. Conclusions and future challenges

8.1. Conclusion

Refinement is a key concept for developing complex systems, since it starts with a very abstract model and incrementally adds new details to the set of requirements. We have outlined an incremental refinement-based approach for formalising medical protocols using RODIN tool. The approach we have taken is not specific to Event B. We believe a similar approach could be taken using others state-based notations such as ASM, TLA^+ and Z etcetera. RODIN proof tool is used to generate the hundreds of proof obligations and to discharge those obligations automatically and interactively. Another key role of the tool is in helping us to discover appropriate gluing invariants to prove the refinements. In summary some key lessons are that incremental development with small refinement steps, appropriate abstractions at each level and powerful tool support are all invaluable in such kind of formal development.

In this report we have shown that formal representation of medical protocol. The formal model of medical protocol is verified and this verified model is not only feasible but also useful for improving the existing medical protocol. We have fully formalised a real-world medical protocols (ECG interpretation) in an incremental refinement-based formalisation process and we have used proof tools to systematically analyse whether the formalisation complies with certain medically relevant protocol properties. The formal verification process has discovered a number of anomalies which all are discussed in previous section. Throughout this process we have obtained the following concrete results:

- A formal specification language Event B that is used for modeling the complex system, is used to model medical practice protocols. Event B is general modeling language tool. The Event B is used to present a formal specification for a real-life medical protocols; ECG interpretation.

- The ECG interpretation protocol is formalised in Event B modeling language. The medical protocol ECG interpretation is used in our study has been developed in incremental way and finally transformed into a concrete formal representation. Each proved refinement level of the formal model of the protocol represents feasibility and correctness.

- In our formal verification process of the ECG interpretation, we have obtained a list of anomalies.

- Verification proofs for the ECG interpretation protocol and properties have proved using RODIN proof tool. Generated proof obligations and proofs show that formal verification of the ECG interpretation protocols is feasible.

- Original protocol of the ECG is also based on some hierarchy, but in that hierarchy some diagnosis is repeating in multiple branches (see in [37]). We have also discovered an optimized hierarchical structure for the ECG interpretation efficiently using incremental refinement approach, which helps to diagnose more efficiently then old techniques and this obtained hierarchical structure is verified through medical experts.

The ECG interpretation protocol is very complex and it interprets various kinds of heart diseases. Improving quality of medical protocol using formal verification tool like highly mathematical based modelling languages; Event B, is the main contribution of our work. We have also discovered an hierarchical structure for the ECG interpretation efficiently that helps to discover a set of conditions that can be very helpful to diagnose particular disease an early stage of the diagnosis without using multiple diagnosis. Our hierarchical tree structure provides more concrete solutions for the ECG interpretation protocol and helps to improve the original ECG interpretation protocol. Our objective behind this work is that if any medical protocol is developed under particular circumstances to handle a set of specific properties according medical experts, formal verification can also meet whether the protocol actually complies with them. This has been the first attempt ever in verifying medical protocols with mathematical rigour with generalized formal modelling tool Event B. The main objective of this approach to test correctness and consistency of the medical protocol using refinement based incremental development. This approach is not only for diagnosis purpose but it may be applicable for covering a large group of other categories (i.e treatment, management, prevention, counseling, evaluation etc.)[3] related to medical protocols.

8.2. Future challenges

This section will focus on some future challenges. First of all we discuss some challenges related to our work for applying formal techniques to improve medical protocol. We will also discuss some existing problems in medical domain, which leads to the challenge of *"living guidelines"* [2].

In this report we have shown that successful implementation for medical protocol improvement of using formal methods. We have completed the entire process of modelling and formalisation of the ECG interpretation protocol and properties, and discharged all generated proof obligations. We have also discovered some hierarchical structure for ECG diagnosis, which helps for improving the ECG protocol.

As we have seen in the entire article, several techniques like modelling, formalising and verifying are used to find anomalies in medical protocols. Some

[3] http://www.guideline.gov/

undecided issue that remain are: what kind of tools are applicable for finding anomalies; when do we need which type of techniques; would it be possible to use verification and validation only in the critical parts of the guideline, and how can we identify these critical parts. Main exiting problem with medical guideline or protocol is quickly changes in protocol within two-three years, which is indicated by Teije et all [2] as future challenges in their paper. After discussion with medical experts, we have found that it is an open problem in this area. However, from last few years medical scientific bodies are updating current guidelines and protocols on-line, and providing up to date information to all users.

We have used Event B modelling language for formalizing the medical protocols. Other languages like Glif, EON, Asbru, GUIDE, or others [10] are more popular languages for formal representation of guideline in medical domain. These languages can also detect anomalies in medical protocols but these are less formal then highly mathematical based modelling languages like Event B, VDM and TLA$^+$ etcetera. Although, we expect that this would yield fewer anomalies during formal development of medical protocols because of the informal nature of these languages. In future we have planed to investigate other kinds of medical protocols using our refinement-based modeling approach. We have found that this approach is more applicable for rectifying the medical protocols as well as to obtain the optimum solutions for diagnosis using refinement based incremental approach rather then used any semi-formal techniques.

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Formal Model of ECG Interpretation using Event-B

Dominique Méry and Neeraj Kumar Singh

An Event-B Specification of Leads_ctx
Generated Date: 25 Nov 2010 @ 03:38:40 PM

CONTEXT Leads_ctx

SETS

LEADS

HState

YesNoState

CONSTANTS

I

II

III

aVR

aVL

aVF

V1

V2

V3

V4

V5

V6

OK

KO

Yes

No

AXIOMS

axm1 : $LEADS = \{I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, V6\}$

axm2 : $\neg I = II$

axm3 : $\neg I = III$

axm4 : $\neg I = aVR$

axm5 : $\neg I = aVL$

axm6 : $\neg I = aVF$

axm7 : $\neg I = V1$

axm8 : $\neg I = V2$

axm9 : $\neg I = V3$

axm10 : $\neg I = V4$

axm11 : $\neg I = V5$

axm12 : $\neg I = V6$

axm13 : $\neg II = III$

axm14 : $\neg II = aVR$

axm15 : $\neg II = aVL$

axm16 : $\neg II = aVF$

axm17 : $\neg II = V1$

axm18 : $\neg II = V2$

axm19 : $\neg II = V3$

axm20 : $\neg II = V4$

axm21 : $\neg II = V5$

axm22 : $\neg II = V6$

axm23 : $\neg III = aVR$

axm24 : $\neg III = aVL$

axm25 : $\neg III = aVF$

axm26 : $\neg III = V1$

axm27 : $\neg III = V2$

axm28 : $\neg III = V3$

axm29 : $\neg III = V4$

axm30 : $\neg III = V5$

axm31 : $\neg III = V6$

axm32 : $\neg aVR = aVL$

axm33 : $\neg aVR = aVF$

axm34 : $\neg aVR = V1$

axm35 : $\neg aVR = V2$

axm36 : $\neg aVR = V3$

axm37 : $\neg aVR = V4$

axm38 : $\neg aVR = V5$

axm39 : $\neg aVR = V6$

axm40 : $\neg aVL = aVF$

axm41 : $\neg aVL = V1$

axm42 : $\neg aVL = V2$

axm43 : $\neg aVL = V3$

axm44 : $\neg aVL = V4$

axm45 : $\neg aVL = V5$

axm46 : $\neg aVL = V6$

axm47 : $\neg aVF = V1$

axm48 : $\neg aVF = V2$

axm49 : $\neg aVF = V3$

axm50 : $\neg aVF = V4$

axm51 : $\neg aVF = V5$

axm52 : $\neg aVF = V6$

axm53 : $\neg V1 = V2$

axm54 : $\neg V1 = V3$

axm55 : $\neg V1 = V4$

axm56 : $\neg V1 = V5$

axm57 : $\neg V1 = V6$

axm58 : $\neg V2 = V3$

axm59 : $\neg V2 = V4$

axm60 : $\neg V2 = V5$

axm61 : $\neg V2 = V6$

axm62 : $\neg V3 = V4$

axm63 : $\neg V3 = V5$

axm64 : $\neg V3 = V6$

axm65 : $\neg V4 = V5$

axm66 : $\neg V4 = V6$

axm67 : $\neg V5 = V6$

axm68 : $HState = \{OK, KO\}$

axm69 : $\neg OK = KO$

axm70 : $YesNoState = \{Yes, No\}$

axm71 : $\neg Yes = No$

END

An Event-B Specification of Disease_Codes_ctx
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CONTEXT Disease_Codes_ctx

SETS

Disease_Codes_Step2

Disease_Codes_Step3

Disease_Codes_Step4

CONSTANTS

First_degree_AV_Block

LBBB

RBBB

A_RBBB

A_LBBB

WPW_Syndrome

Brugada_Syndrome

RV_Dysplasia

IVCD

Acute_inferior_MI

Acute_anterior_MI

STEMI

Troponin

CK_MB

Non_STEMI

Ischemia

NDS2

NDS3

NDS4

AXIOMS

axm1 : $Disease\_Codes\_Step2 = \{First\_degree\_AV\_Block, LBBB, RBBB, NDS2\}$

axm2 : $\neg First\_degree\_AV\_Block = LBBB$

axm3 : $\neg First\_degree\_AV\_Block = RBBB$

axm43 : $\neg First\_degree\_AV\_Block = NDS2$

axm4 : $\neg LBBB = RBBB$

axm44 : $\neg LBBB = NDS2$

axm45 : $\neg RBBB = NDS2$

axm5 : $Disease\_Codes\_Step3 = \{A\_RBBB, A\_LBBB, WPW\_Syndrome, Brugada\_Syndrome, RV\_Dysplasia, IVCD, NDS3\}$
No. of Disease Step 3 (NDS3)

axm6 : $\neg A\_RBBB = A\_LBBB$

axm7 : $\neg A\_RBBB = WPW\_Syndrome$

axm8 : $\neg A\_RBBB = Brugada\_Syndrome$

axm9 : $\neg A\_RBBB = RV\_Dysplasia$

axm10 : $\neg A\_RBBB = IVCD$
axm46 : $\neg A\_RBBB = NDS3$
axm11 : $\neg A\_LBBB = WPW\_Syndrome$
axm12 : $\neg A\_LBBB = Brugada\_Syndrome$
axm13 : $\neg A\_LBBB = RV\_Dysplasia$
axm14 : $\neg A\_LBBB = IVCD$
axm47 : $\neg A\_LBBB = NDS3$
axm15 : $\neg WPW\_Syndrome = Brugada\_Syndrome$
axm16 : $\neg WPW\_Syndrome = RV\_Dysplasia$
axm17 : $\neg WPW\_Syndrome = IVCD$
axm48 : $\neg WPW\_Syndrome = NDS3$
axm18 : $\neg Brugada\_Syndrome = RV\_Dysplasia$
axm19 : $\neg Brugada\_Syndrome = IVCD$
axm49 : $\neg Brugada\_Syndrome = NDS3$
axm20 : $\neg RV\_Dysplasia = IVCD$
axm50 : $\neg RV\_Dysplasia = NDS3$
axm51 : $\neg IVCD = NDS3$
axm21 : $Disease\_Codes\_Step4 = \{Acute\_inferior\_MI, Acute\_anterior\_MI, STEMI, Troponin, CK\_MB, Non\_STEMI, Ischemia, NDS4\}$
axm22 : $\neg Acute\_inferior\_MI = Acute\_anterior\_MI$
axm23 : $\neg Acute\_inferior\_MI = STEMI$
axm24 : $\neg Acute\_inferior\_MI = Troponin$
axm25 : $\neg Acute\_inferior\_MI = CK\_MB$
axm26 : $\neg Acute\_inferior\_MI = Non\_STEMI$
axm27 : $\neg Acute\_inferior\_MI = Ischemia$
axm52 : $\neg Acute\_inferior\_MI = NDS4$
axm28 : $\neg Acute\_anterior\_MI = STEMI$
axm29 : $\neg Acute\_anterior\_MI = Troponin$
axm30 : $\neg Acute\_anterior\_MI = CK\_MB$
axm31 : $\neg Acute\_anterior\_MI = Non\_STEMI$
axm32 : $\neg Acute\_anterior\_MI = Ischemia$
axm53 : $\neg Acute\_anterior\_MI = NDS4$
axm33 : $\neg STEMI = Troponin$
axm34 : $\neg STEMI = CK\_MB$
axm35 : $\neg STEMI = Non\_STEMI$
axm36 : $\neg STEMI = Ischemia$
axm54 : $\neg STEMI = NDS4$
axm37 : $\neg Troponin = CK\_MB$
axm38 : $\neg Troponin = Non\_STEMI$
axm39 : $\neg Troponin = Ischemia$
axm56 : $\neg Troponin = NDS4$
axm40 : $\neg CK\_MB = Non\_STEMI$
axm41 : $\neg CK\_MB = Ischemia$
axm55 : $\neg CK\_MB = NDS4$
axm42 : $\neg Non\_STEMI = Ischemia$
axm57 : $\neg Non\_STEMI = NDS4$
axm58 : $\neg Ischemia = NDS4$

END

An Event-B Specification of Step1
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MACHINE Step1

SEES Leads_ctx

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`PP_Interval`

`RR_Interval`

INVARIANTS

`inv1` : $RR\_Int\_equidistant \in LEADS \rightarrow BOOL$
RR intervals are equidistant

`inv2` : $PP\_Int\_equidistant \in LEADS \rightarrow BOOL$
PP intervals are equidistant

`inv3` : $P\_Positive \in LEADS \rightarrow BOOL$
P wave positive

`inv4` : $Sinus \in YesNoState$
Sinus State

`inv5` : $PP\_Interval \in LEADS \rightarrow \mathbb{N}$

`inv6` : $RR\_Interval \in LEADS \rightarrow \mathbb{N}$

`inv7` : $P\_Positive(II) = FALSE \Rightarrow Sinus = No$

`inv8` : $((\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor RR\_Int\_equidistant(l) = FALSE \lor RR\_Interval(l) \neq PP\_Interval(l)) \lor P\_Positive(II) = FALSE) \Rightarrow Sinus = No$

`inv9` : $Sinus = Yes \Rightarrow ((\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land RR\_Int\_equidistant(l) = TRUE \land RR\_Interval(l) = PP\_Interval(l)) \land P\_Positive(II) = TRUE)$

EVENTS

Initialisation

begin

`act1` : $RR\_Int\_equidistant :\in LEADS \rightarrow BOOL$

`act2` : $PP\_Int\_equidistant :\in LEADS \rightarrow BOOL$

`act3` : $P\_Positive :\in LEADS \rightarrow BOOL$

`act4` : $Sinus := No$

`act5` : $PP\_Interval :\in LEADS \rightarrow \mathbb{N}$

`act6` : $RR\_Interval :\in LEADS \rightarrow \mathbb{N}$

end

Event $Rhythm\_test\_TRUE \mathrel{\widehat{=}}$
Sinus Rhythm

when

`grd4` : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

then

`act1` : $Sinus := Yes$

end

Event $Rhythm\_test\_FALSE \mathrel{\widehat{=}}$
Abnormal Rhythm

when

`grd2` : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

then

`act1` : $Sinus := No$

end

END

An Event-B Specification of Step1_Rate_Ref
Generated Date: 25 Nov 2010 @ 03:39:01 PM

MACHINE Step1_Rate_Ref

REFINES Step1

SEES Leads_ctx

VARIABLES

- `RR_Int_equidistant` RR Interval
- `PP_Int_equidistant` PP Interval
- `P_Positive` P wave positive or negative
- `Sinus` Sinus Rhythm
- `Heart_Rate` Heart Rate in BPM
- `Heart_State` OK or KO for heart state after ECG Interpretation
- `PP_Interval`
- `RR_Interval`

INVARIANTS

- inv1 : $Heart\_Rate \in 1 \,..\, 300$
- inv2 : $Heart\_State \in HState$
- inv3 : $Heart\_Rate \in 60 \,..\, 100 \land Sinus = Yes \Rightarrow Heart\_State = OK$
- inv5 : $Heart\_Rate \in 1 \,..\, 300 \setminus 60 \,..\, 100 \land Sinus = Yes \Rightarrow Heart\_State = KO$
- inv6 : $Heart\_Rate \in 60 \,..\, 100 \land Sinus = No \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

begin

- act1 : $RR\_Int\_equidistant :\in LEADS \rightarrow BOOL$
- act2 : $PP\_Int\_equidistant :\in LEADS \rightarrow BOOL$
- act3 : $P\_Positive :\in LEADS \rightarrow BOOL$
- act4 : $Sinus := No$
- act5 : $PP\_Interval :\in LEADS \rightarrow \mathbb{N}$
- act6 : $RR\_Interval :\in LEADS \rightarrow \mathbb{N}$
- act7 : $Heart\_Rate :\in 1 \,..\, 300$
- act8 : $Heart\_State := KO$

end

Event $Rhythm\_test\_TRUE \;\widehat{=}$
Sinus Rhythm with Normal Rate

refines $Rhythm\_test\_TRUE$

any

$rate$

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land RR\_Int\_equidistant(l) = TRUE \land RR\_Interval(l) = PP\_Interval(l)) \land P\_Positive(II) = TRUE$

grd5 : $rate \in 60 \,..\, 100$
60..100 is the range of normal heart rate

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := OK$

end

Event $Rhythm\_test\_FALSE \mathrel{\widehat{=}}$
Abnormal Rhythm with Rate

refines $Rhythm\_test\_FALSE$

any

$rate$

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $rate \in 1 \,..\, 300$

then

act1 : $Sinus := No$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event $Rhythm\_test\_TRUE\_Rate \mathrel{\widehat{=}}$
Sinus Rhythm with abnormal Rate

refines $Rhythm\_test\_TRUE$

any

$rate$

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd5 : $rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

END

An Event-B Specification of Step2_PR_Blocks_Ref
Generated Date: 25 Nov 2010 @ 03:39:03 PM

MACHINE Step2_PR_Blocks_Ref

REFINES Step1_Rate_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

- `RR_Int_equidistant` RR Interval
- `PP_Int_equidistant` PP Interval
- `P_Positive` P wave positive or negative
- `Sinus` Sinus Rhythm
- `Heart_Rate` Heart Rate in BPM
- `Heart_State` OK or KO for heart state after ECG Interpretation
- `PR_Int` PR Interval
- `Disease_step2` At level 2 Disease Codes
- `QRS_Int` QRS Interval
- `PP_Interval`
- `RR_Interval`

INVARIANTS

- inv1 : $PR\_Int \in 120 \,..\, 250$
- inv2 : $Disease\_step2 \in Disease\_Codes\_Step2$
- inv3 : $QRS\_Int \in 50 \,..\, 150$
- inv4 : $Sinus = Yes \wedge PR\_Int > 200 \wedge Disease\_step2 = First\_degree\_AV\_Block$
  $\Rightarrow Heart\_State = KO$
- inv5 : $Sinus = Yes \wedge QRS\_Int \geq 120 \wedge Disease\_step2 \in \{LBBB, RBBB\}$
  $\Rightarrow Heart\_State = KO$
- inv7 : $Heart\_Rate \in 60 \,..\, 100 \wedge Sinus = Yes \wedge PR\_Int \leq 200 \wedge QRS\_Int < 120$
  $\Rightarrow Heart\_State = OK$

EVENTS

Initialisation
extended

begin

- act1 : $\mathtt{RR\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
- act2 : $\mathtt{PP\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
- act3 : $\mathtt{P\_Positive} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
- act4 : $\mathtt{Sinus} := \mathtt{No}$
- act5 : $\mathtt{PP\_Interval} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
- act6 : $\mathtt{RR\_Interval} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
- act7 : $\mathtt{Heart\_Rate} :\in 1 \,..\, 300$
- act8 : $\mathtt{Heart\_State} := \mathtt{KO}$
- act9 : $PR\_Int := 120$
- act10 : $Disease\_step2 := NDS2$
- act11 : $QRS\_Int := 50$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

refines *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd4 : $rate \in 60 .. 100$
60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$
Heart is Normal if PR $\leq$ 200 *QRS_Int ¡ 120*
$HeartisNormalifQRS < 120$

grd6
then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $rate \in 1 .. 300$

then

act1 : Sinus := No

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

refines *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd5 : $rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event $PR\_Test \mathrel{\widehat{=}}$

PR Interval Test

any

pr

where

grd1 : $pr \in 120 \,..\, 220$

time interval in (ms.)

grd2 : $pr > 200$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

then

act1 : $PR\_Int := pr$

act2 : $Disease\_step2 := First\_degree\_AV\_Block$

end

Event $QRS\_Test \mathrel{\widehat{=}}$

QRS Complex Interval Test

any

qrs

where

grd1 : $qrs \in 50 \,..\, 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

then

act1 : $QRS\_Int := qrs$

act2 : $Disease\_step2 :| Disease\_step2' \in \{LBBB, RBBB\}$

end

END

An Event-B Specification of Step2_Blocks_Ref
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MACHINE Step2_Blocks_Ref

REFINES Step2_PR_Blocks_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

`RR_Int_equidistant` RR Interval
`PP_Int_equidistant` PP Interval
`P_Positive` P wave positive or negative
`Sinus` Sinus Rhythm
`Heart_Rate` Heart Rate in BPM
`Heart_State` OK or KO for heart state after ECG Interpretation
`PR_Int` PR Interval
`Disease_step2` At level 2 Disease Codes
`QRS_Int` QRS Interval
`M_Shape_Complex` M-shaped complex in Leads
`Slurred_S` Slurred S wave in Leads
`Notched_R` Notched R wave in Leads
`Small_R_QS` A small R or QS wave in V1 and V2
`Slurred_S_duration` Slurred S duration
`PP_Interval`
`RR_Interval`

INVARIANTS

inv1 : $M\_Shape\_Complex \in LEADS \rightarrow BOOL$
inv2 : $Slurred\_S \in LEADS \rightarrow BOOL$
inv3 : $Notched\_R \in LEADS \rightarrow BOOL$
inv4 : $Small\_R\_QS \in LEADS \rightarrow BOOL$
inv5 : $Slurred\_S\_duration \in LEADS \rightarrow \mathbb{N}_1$
inv6 : $Sinus = Yes \land Disease\_step2 = First\_degree\_AV\_Block \Rightarrow Heart\_State = KO$
inv7 : $Sinus = Yes \land Disease\_step2 = LBBB \Rightarrow Heart\_State = KO$
inv8 : $Sinus = Yes \land Disease\_step2 = RBBB \Rightarrow Heart\_State = KO$

EVENTS

Initialisation
extended

begin

act1 : $\mathtt{RR\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act2 : $\mathtt{PP\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act3 : $\mathtt{P\_Positive} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act4 : $\mathtt{Sinus} := \mathtt{No}$
act5 : $\mathtt{PP\_Interval} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act6 : $\mathtt{RR\_Interval} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act7 : $\mathtt{Heart\_Rate} :\in 1 \,..\, 300$

act8 : $\texttt{Heart\_State} := \texttt{KO}$
act9 : $\texttt{PR\_Int} := 120$
act10 : $\texttt{Disease\_step2} := \texttt{NDS2}$
act11 : $\texttt{QRS\_Int} := 50$
act12 : $Notched\_R :\in LEADS \rightarrow BOOL$
act13 : $Small\_R\_QS :\in LEADS \rightarrow BOOL$
act14 : $Slurred\_S\_duration :\in LEADS \rightarrow \mathbb{N}_1$
act15 : $M\_Shape\_Complex :\in LEADS \rightarrow BOOL$
act16 : $Slurred\_S :\in LEADS \rightarrow BOOL$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

refines *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd4 : $rate \in 60 \,..\, 100$
60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$
Heart is Normal if PR $\leq$ 200 QRS_Int ¡ 120
$HeartisNormalifQRS < 120$

grdgrd7 : $Disease\_step2 = NDS2$

then

act1 : $Sinus := Yes$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{PP\_Int\_equidistant(l)} = \texttt{FALSE} \lor$
$\texttt{RR\_Int\_equidistant(l)} = \texttt{FALSE} \lor$
$\texttt{RR\_Interval(l)} \neq \texttt{PP\_Interval(l)})$
$\lor$
$\texttt{P\_Positive(II)} = \texttt{FALSE}$

grd2 : $\texttt{rate} \in 1 \,..\, 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l})) \land \texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$

grd5 : $\texttt{rate} \in 1 \mathrel{..} 300 \setminus 60 \mathrel{..} 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

then

act1 : $\texttt{Sinus} := \texttt{Yes}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\texttt{pr} \in 120 \mathrel{..} 220$

time interval in (ms.)

grd2 : $\texttt{pr} > 200$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{PR\_Int} := \texttt{pr}$

act2 : $\texttt{Disease\_step2} := \texttt{First\_degree\_AV\_Block}$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

refines *QRS_Test*

any

qrs

where

grd1 : $qrs \in 50 \mathrel{..} 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $Notched\_R(I) = TRUE \wedge$
$Notched\_R(V5) = TRUE \wedge$
$Notched\_R(V6) = TRUE$

Right Bundle Branch Block (RBBB)

grd6 : $Small\_R\_QS(V1) = TRUE \wedge$
$Small\_R\_QS(V2) = TRUE$

then

act1 : $QRS\_Int := qrs$

act2 : $Disease\_step2 := LBBB$

end

Event $QRS\_Test\_RBBB \ \widehat{=}$

Right Bundle Branch Block (RBBB)

refines QRS_Test

any

qrs

where

grd1 : $qrs \in 50 \,..\, 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $M\_Shape\_Complex(V1) = TRUE \wedge$
$M\_Shape\_Complex(V2) = TRUE$

grd7 : $Slurred\_S(I) = TRUE \wedge$
$Slurred\_S(V5) = TRUE \wedge$
$Slurred\_S(V6) = TRUE$

grd8 : $Slurred\_S\_duration(I) > 40 \wedge$
$Slurred\_S\_duration(V5) > 40 \wedge$
$Slurred\_S\_duration(V6) > 40$

then

act1 : $QRS\_Int := qrs$

act2 : $Disease\_step2 := RBBB$

end

END

An Event-B Specification of Step3
Generated Date: 25 Nov 2010 @ 03:39:09 PM

MACHINE Step3

REFINES Step2_Blocks_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`PP_Interval`

`RR_Interval`

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

INVARIANTS

inv1 : $Delta\_Wave \in \mathbb{N}$

inv2 : $Disease\_step3 \in Disease\_Codes\_Step3$

inv3 : $Sinus = Yes \land Disease\_step3 = WPW\_Syndrome \Rightarrow Heart\_State = KO$

inv4 : $ST\_elevation \in LEADS \rightarrow BOOL$

inv5 : $Sinus = Yes \land Disease\_step3 = Brugada\_Syndrome \Rightarrow Heart\_State = KO$

inv6 : $Epsilon\_Wave \in LEADS \rightarrow BOOL$

inv7 : $Sinus = Yes \land Disease\_step3 = RV\_Dysplasia \Rightarrow Heart\_State = KO$

inv8 : $Sinus = Yes \land Disease\_step3 = IVCD \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR\_Int\_equidistant :\in LEADS \rightarrow BOOL$

act2 : $PP\_Int\_equidistant :\in LEADS \rightarrow BOOL$

act3 : $P\_Positive :\in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP\_Interval :\in LEADS \rightarrow \mathbb{N}$
act6 : $RR\_Interval :\in LEADS \rightarrow \mathbb{N}$
act7 : $Heart\_Rate :\in 1 .. 300$
act8 : $Heart\_State := KO$
act9 : $PR\_Int := 120$
act10 : $Disease\_step2 := NDS2$
act11 : $QRS\_Int := 50$
act12 : $Notched\_R :\in LEADS \rightarrow BOOL$
act13 : $Small\_R\_QS :\in LEADS \rightarrow BOOL$
act14 : $Slurred\_S\_duration :\in LEADS \rightarrow \mathbb{N}_1$
act15 : $M\_Shape\_Complex :\in LEADS \rightarrow BOOL$
act16 : $Slurred\_S :\in LEADS \rightarrow BOOL$
act17 : $ST\_elevation :\in LEADS \rightarrow BOOL$
act18 : $Epsilon\_Wave :\in LEADS \rightarrow BOOL$
act19 : $Delta\_Wave := 0$
act20 : $Disease\_step3 := NDS3$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

refines *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge RR\_Int\_equidistant(l) = TRUE \wedge RR\_Interval(l) = PP\_Interval(l)) \wedge P\_Positive(II) = TRUE$
grd4 : $rate \in 60 .. 100$
60..100 is the range of normal heart rate
grd5 : $PR\_Int \leq 200$
Heart is Normal if PR $\leq$ 200 *QRS_Int ¡ 120*
$HeartisNormalifQRS < 120$
grd6grd7 : $Disease\_step2 = NDS2$
grd8 : $Disease\_step3 = NDS3$

then

act1 : $Sinus := Yes$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $rate \in 1 \,..\, 300$

then

act1 : $Sinus := No$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

refines *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd5 : $rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $Disease\_step3 = WPW\_Syndrome \lor Disease\_step3 = Brugada\_Syndrome \lor$
$Disease\_step3 = RV\_Dysplasia \lor Disease\_step3 = IVCD$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $pr \in 120 \,..\, 220$
time interval in (ms.)

grd2 : $pr > 200$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

then

act1 : $PR\_Int := pr$

act2 : $Disease\_step2 := First\_degree\_AV\_Block$

end

Event $QRS\_Test\_LBBB \mathrel{\widehat{=}}$
QRS Complex Interval Test

refines QRS_Test_LBBB

any

qrs

where

grd1 : $qrs \in 50 \mathrel{..} 150$
grd2 : $qrs \geq 120$
grd3 : $Sinus = Yes$
grd4 : $Heart\_State = KO$
grd5 : $Notched\_R(I) = TRUE \land$
$Notched\_R(V5) = TRUE \land$
$Notched\_R(V6) = TRUE$
Right Bundle Branch Block (RBBB)
grd6 : $Small\_R\_QS(V1) = TRUE \land$
$Small\_R\_QS(V2) = TRUE$

then

act1 : $QRS\_Int := qrs$
act2 : $Disease\_step2 := LBBB$

end

Event $QRS\_Test\_RBBB \mathrel{\widehat{=}}$
Right Bundle Branch Block (RBBB)

refines QRS_Test_RBBB

any

qrs

where

grd1 : $qrs \in 50 \mathrel{..} 150$
grd2 : $qrs \geq 120$
grd3 : $Sinus = Yes$
grd4 : $Heart\_State = KO$
grd5 : $M\_Shape\_Complex(V1) = TRUE \land$
$M\_Shape\_Complex(V2) = TRUE$
grd7 : $Slurred\_S(I) = TRUE \land$
$Slurred\_S(V5) = TRUE \land$
$Slurred\_S(V6) = TRUE$
grd8 : $Slurred\_S\_duration(I) > 40 \land$
$Slurred\_S\_duration(V5) > 40 \land$
$Slurred\_S\_duration(V6) > 40$

then

act1 : $QRS\_Int := qrs$
act2 : $Disease\_step2 := RBBB$

end

Event $QRS\_Test\_Atypical\_RLBBB\_WPW\_Syndrome \mathrel{\widehat{=}}$
QRS Test for Atypical LBBB RBBB

any

$sympt$

d_wave

where

grd1 : $QRS\_Int \geq 110$

grd2 : $sympt = A\_RBBB \lor sympt = A\_LBBB$

grd3 : $d\_wave \in \mathbb{N}$

grd4 : $(d\_wave + PR\_Int) \leq 120$

Delta Wave + PR $\leq$ 120 $Heart\_State = KO$

grd5

then

act2 : $Delta\_Wave := d\_wave$

act3 : $Disease\_step3 := WPW\_Syndrome$

end

Event $QRS\_Test\_Atypical\_RBBB\_Brugada\_Syndrome \ \widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

any

$sympt$

dis

where

grd1 : $sympt = A\_RBBB$

grd2 : $Heart\_State = KO$

grd3 : $QRS\_Int \geq 110$

grd4 : $Slurred\_S(V5) = FALSE \land$
$Slurred\_S(V6) = FALSE$

grd5 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, NDS3\}$

grd6 : $ST\_elevation(V1) = TRUE \land$
$ST\_elevation(V2) = TRUE$

grd7 : $Sinus = Yes$

then

act1 : $Disease\_step3 := Brugada\_Syndrome$

end

Event $QRS\_Test\_Atypical\_RBBB\_RV\_Dysplasia \ \widehat{=}$

Right Ventricular Dysplasia

any

$sympt$

dis

where

grd1 : $sympt = A\_RBBB$

grd2 : $Heart\_State = KO$

grd3 : $QRS\_Int \geq 110$

grd4 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, Brugada\_Syndrome, NDS3\}$

grd5 : $Epsilon\_Wave(V1) = TRUE \land$
$Epsilon\_Wave(V3) = TRUE$

then

act1 : $Disease\_step3 := RV\_Dysplasia$

end

Event $QRS\_Test\_Atypical\_RBBB\_IVCD \ \widehat{=}$

IVCD diagnosis

any

dis

where

grd1 : $QRS\_Int \geq 110$

grd2 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, Brugada\_Syndrome, RV\_Dysplasia, NDS3\}$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step3 := IVCD$

end

END

An Event-B Specification of Step4
Generated Date: 25 Nov 2010 @ 03:39:11 PM

MACHINE Step4

REFINES Step3

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

- `RR_Int_equidistant` RR Interval
- `PP_Int_equidistant` PP Interval
- `P_Positive` P wave positive or negative
- `Sinus` Sinus Rhythm
- `Heart_Rate` Heart Rate in BPM
- `Heart_State` OK or KO for heart state after ECG Interpretation
- `PR_Int` PR Interval
- `Disease_step2` At level 2 Disease Codes
- `QRS_Int` QRS Interval
- `M_Shape_Complex` M-shaped complex in Leads
- `Slurred_S` Slurred S wave in Leads
- `Notched_R` Notched R wave in Leads
- `PP_Interval`
- `RR_Interval`
- `Small_R_QS` A small R or QS wave in V1 and V2
- `Slurred_S_duration` Slurred S duration
- `Delta_Wave` Delta Wave
- `Disease_step3`
- `ST_elevation` ST segment elevation (Coved or Saddle-back)
- `Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
- `ST_seg_ele` ST segment for elevation 1mm=0.1mV
- `Disease_step4`

INVARIANTS

- inv1 : $ST\_seg\_ele \in LEADS \rightarrow \mathbb{N}$
- inv2 : $Disease\_step4 \in Disease\_Codes\_Step4$

EVENTS

Initialisation

begin

- act1 : $RR\_Int\_equidistant :\in LEADS \rightarrow BOOL$
- act2 : $PP\_Int\_equidistant :\in LEADS \rightarrow BOOL$
- act3 : $P\_Positive :\in LEADS \rightarrow BOOL$
- act4 : $Sinus := No$
- act5 : $PP\_Interval :\in LEADS \rightarrow \mathbb{N}$
- act6 : $RR\_Interval :\in LEADS \rightarrow \mathbb{N}$
- act7 : $Heart\_Rate :\in 1 \,..\, 300$
- act8 : $Heart\_State := KO$

act9 : $PR\_Int := 120$
act10 : $Disease\_step2 := NDS2$
act11 : $QRS\_Int := 50$
act12 : $Notched\_R :\in LEADS \rightarrow BOOL$
act13 : $Small\_R\_QS :\in LEADS \rightarrow BOOL$
act14 : $Slurred\_S\_duration :\in LEADS \rightarrow \mathbb{N}_1$
act15 : $M\_Shape\_Complex :\in LEADS \rightarrow BOOL$
act16 : $Slurred\_S :\in LEADS \rightarrow BOOL$
act17 : $ST\_elevation :\in LEADS \rightarrow BOOL$
act18 : $Epsilon\_Wave :\in LEADS \rightarrow BOOL$
act19 : $Delta\_Wave := 0$
act20 : $Disease\_step3 := NDS3$
act21 : $ST\_seg\_ele :\in LEADS \rightarrow \mathbb{N}$
act22 : $Disease\_step4 := NDS4$

end

Event $Rhythm\_test\_TRUE \widehat{=}$
Sinus Rhythm with Normal Rate

extends $Rhythm\_test\_TRUE$

any
rate

where
grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$
grd4 : $rate \in 60 .. 100$
60..100 is the range of normal heart rate
grd5 : $PR\_Int \leq 200$
Heart is Normal if PR $\leq$ 200 QRS_Int < 120
$HeartisNormalifQRS < 120$
grd6grd7 : $Disease\_step2 = NDS2$
grd8 : $Disease\_step3 = NDS3$

then
act1 : $Sinus := Yes$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := OK$

end

Event $Rhythm\_test\_FALSE \widehat{=}$
Abnormal Rhythm with Rate

extends $Rhythm\_test\_FALSE$

any
rate

where
grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $\texttt{rate} \in 1 \,..\, 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l})) \land \texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$

grd5 : $\texttt{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $\texttt{Disease\_step3} = \texttt{WPW\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{Brugada\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{RV\_Dysplasia} \lor \texttt{Disease\_step3} = \texttt{IVCD}$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\texttt{pr} \in 120 \,..\, 220$

time interval in (ms.)

grd2 : $\texttt{pr} > 200$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{PR\_Int} := \texttt{pr}$

act2 : $\texttt{Disease\_step2} := \texttt{First\_degree\_AV\_Block}$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\mathtt{qrs} \in 50 \,..\, 150$

grd2 : $\mathtt{qrs} \geq 120$

grd3 : $\mathtt{Sinus} = \mathtt{Yes}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd5 : $\mathtt{Notched\_R(I)} = \mathtt{TRUE} \land$
$\mathtt{Notched\_R(V5)} = \mathtt{TRUE} \land$
$\mathtt{Notched\_R(V6)} = \mathtt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\mathtt{Small\_R\_QS(V1)} = \mathtt{TRUE} \land$
$\mathtt{Small\_R\_QS(V2)} = \mathtt{TRUE}$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$

act2 : $\mathtt{Disease\_step2} := \mathtt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

refines *QRS_Test_RBBB*

any

qrs

where

grd1 : $qrs \in 50 \,..\, 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $M\_Shape\_Complex(V1) = TRUE \land$
$M\_Shape\_Complex(V2) = TRUE$

grd7 : $Slurred\_S(I) = TRUE \land$
$Slurred\_S(V5) = TRUE \land$
$Slurred\_S(V6) = TRUE$

grd8 : $Slurred\_S\_duration(I) > 40 \land$
$Slurred\_S\_duration(V5) > 40 \land$
$Slurred\_S\_duration(V6) > 40$

then

act1 : $QRS\_Int := qrs$

act2 : $Disease\_step2 := RBBB$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt

d_wave

where

grd1 : $\mathtt{QRS\_Int} \geq 110$

grd2 : $\mathtt{sympt} = \mathtt{A\_RBBB} \lor \mathtt{sympt} = \mathtt{A\_LBBB}$

grd3 : $\mathtt{d\_wave} \in \mathbb{N}$

grd4 : $(\mathtt{d\_wave} + \mathtt{PR\_Int}) \leq 120$

Delta Wave + PR $\leq$ 120 Heart_State = KO

grd5then

act2 : $\mathtt{Delta\_Wave} := \mathtt{d\_wave}$

act3 : $\mathtt{Disease\_step3} := \mathtt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

refines *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt

dis

where

grd1 : $sympt = A\_RBBB$

grd2 : $Heart\_State = KO$

grd3 : $QRS\_Int \geq 110$

grd4 : $Slurred\_S(V5) = FALSE \wedge$
$Slurred\_S(V6) = FALSE$

grd5 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, NDS3\}$

grd6 : $ST\_elevation(V1) = TRUE \wedge$
$ST\_elevation(V2) = TRUE$

grd7 : $Sinus = Yes$

then

act1 : $Disease\_step3 := Brugada\_Syndrome$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$

Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt

dis

where

grd1 : $\mathtt{sympt} = \mathtt{A\_RBBB}$

grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd3 : $\mathtt{QRS\_Int} \geq 110$

grd4 : $\mathtt{dis} \in \mathtt{Disease\_Codes\_Step3} \setminus \{\mathtt{WPW\_Syndrome}, \mathtt{Brugada\_Syndrome}, \mathtt{NDS3}\}$

grd5 : $\mathtt{Epsilon\_Wave(V1)} = \mathtt{TRUE} \wedge$
$\mathtt{Epsilon\_Wave(V3)} = \mathtt{TRUE}$

then

act1 : $\mathtt{Disease\_step3} := \mathtt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$

IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_Yes* $\widehat{=}$

ST segment elevation...

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

1000 micrometr = 1mm = 0.1mV

then

act1 : $Disease\_step4 :| Disease\_step4' \in Disease\_Codes\_Step4$

end

Event *ST_seg_elevation_No* $\widehat{=}$

ST segment elevation...

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

$\forall l1, k1 \cdot l1 \in \{II, III, aVF\} \wedge k1 \in \{II, III, aVF\} \wedge (ST\_elevation(l1) = FALSE \wedge ST\_elevation(k1) = FALSE) \wedge (ST\_seg\_ele(l1) < 1000 \wedge ST\_seg\_ele(k1) < 1000) \Rightarrow l1 \neq k1)$

then

act1 : $Disease\_step4 :| Disease\_step4' \in Disease\_Codes\_Step4$

end

END

An Event-B Specification of Step4_ST_MI_Ref
Generated Date: 25 Nov 2010 @ 03:39:14 PM

MACHINE Step4_ST_MI_Ref

REFINES Step4

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

`RR_Int_equidistant` RR Interval
`PP_Int_equidistant` PP Interval
`P_Positive` P wave positive or negative
`Sinus` Sinus Rhythm
`Heart_Rate` Heart Rate in BPM
`Heart_State` OK or KO for heart state after ECG Interpretation
`PR_Int` PR Interval
`Disease_step2` At level 2 Disease Codes
`QRS_Int` QRS Interval
`M_Shape_Complex` M-shaped complex in Leads
`Slurred_S` Slurred S wave in Leads
`Notched_R` Notched R wave in Leads
`PP_Interval`
`RR_Interval`
`Small_R_QS` A small R or QS wave in V1 and V2
`Slurred_S_duration` Slurred S duration
`Delta_Wave` Delta Wave
`Disease_step3`
`ST_elevation` ST segment elevation (Coved or Saddle-back)
`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
`ST_seg_ele` ST segment for elevation 1mm=0.1mV
`Disease_step4`
`ST_depression`

INVARIANTS

`inv1` : $ST\_depression \in LEADS \rightarrow \mathbb{N}$
`inv2` : $Sinus = Yes \wedge Disease\_step4 \in \{Acute\_inferior\_MI, Acute\_anterior\_MI\} \Rightarrow Heart\_State = KO$
`inv3` : $Sinus = Yes \wedge Disease\_step4 = STEMI \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

begin

`act1` : $RR\_Int\_equidistant :\in LEADS \rightarrow BOOL$
`act2` : $PP\_Int\_equidistant :\in LEADS \rightarrow BOOL$
`act3` : $P\_Positive :\in LEADS \rightarrow BOOL$
`act4` : $Sinus := No$
`act5` : $PP\_Interval :\in LEADS \rightarrow \mathbb{N}$

act6 : $RR\_Interval :\in LEADS \rightarrow \mathbb{N}$
act7 : $Heart\_Rate :\in 1 .. 300$
act8 : $Heart\_State := KO$
act9 : $PR\_Int := 120$
act10 : $Disease\_step2 := NDS2$
act11 : $QRS\_Int := 50$
act12 : $Notched\_R :\in LEADS \rightarrow BOOL$
act13 : $Small\_R\_QS :\in LEADS \rightarrow BOOL$
act14 : $Slurred\_S\_duration :\in LEADS \rightarrow \mathbb{N}_1$
act15 : $M\_Shape\_Complex :\in LEADS \rightarrow BOOL$
act16 : $Slurred\_S :\in LEADS \rightarrow BOOL$
act17 : $ST\_elevation :\in LEADS \rightarrow BOOL$
act18 : $Epsilon\_Wave :\in LEADS \rightarrow BOOL$
act19 : $Delta\_Wave := 0$
act20 : $Disease\_step3 := NDS3$
act21 : $ST\_seg\_ele :\in LEADS \rightarrow \mathbb{N}$
act22 : $Disease\_step4 := NDS4$
act57 : $ST\_depression :\in LEADS \rightarrow \mathbb{N}$

end

Event $Rhythm\_test\_TRUE \widehat{=}$
Sinus Rhythm with Normal Rate

refines $Rhythm\_test\_TRUE$

any

$rate$

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge RR\_Int\_equidistant(l) = TRUE \wedge RR\_Interval(l) = PP\_Interval(l)) \wedge P\_Positive(II) = TRUE$
grd4 : $rate \in 60 .. 100$
60..100 is the range of normal heart rate
grd5 : $PR\_Int \leq 200$
Heart is Normal if PR $\leq$ 200 QRS_Int ¡ 120
$HeartisNormalifQRS < 120$
grd6grd7 : $Disease\_step2 = NDS2$
grd8 : $Disease\_step3 = NDS3$
grd9 : $Disease\_step4 = NDS4$

then

act1 : $Sinus := Yes$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := OK$

end

Event $Rhythm\_test\_FALSE \widehat{=}$
Abnormal Rhythm with Rate

extends $Rhythm\_test\_FALSE$

any

rate

where

grd1 : $(\forall l \cdot l \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \Rightarrow \mathtt{PP\_Int\_equidistant}(l) = \mathtt{FALSE} \lor$
$\mathtt{RR\_Int\_equidistant}(l) = \mathtt{FALSE} \lor$
$\mathtt{RR\_Interval}(l) \neq \mathtt{PP\_Interval}(l))$
$\lor$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{FALSE}$

grd2 : $\mathtt{rate} \in 1 \,..\, 300$

then

act1 : Sinus := No

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \land \mathtt{PP\_Int\_equidistant}(l) = \mathtt{TRUE} \land$
$\mathtt{RR\_Int\_equidistant}(l) = \mathtt{TRUE} \land$
$\mathtt{RR\_Interval}(l) = \mathtt{PP\_Interval}(l))$
$\land$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{TRUE}$

grd5 : $\mathtt{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $\mathtt{Disease\_step3} = \mathtt{WPW\_Syndrome} \lor \mathtt{Disease\_step3} = \mathtt{Brugada\_Syndrome} \lor$
$\mathtt{Disease\_step3} = \mathtt{RV\_Dysplasia} \lor \mathtt{Disease\_step3} = \mathtt{IVCD}$

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\mathtt{pr} \in 120 \,..\, 220$
time interval in (ms.)

grd2 : $\mathtt{pr} > 200$

grd3 : Sinus = Yes

grd4 : Heart_State = KO

then

act1 : PR_Int := pr

act2 : Disease_step2 := First_degree_AV_Block

end

Event $QRS\_Test\_LBBB \mathrel{\widehat{=}}$
QRS Complex Interval Test

extends QRS_Test_LBBB

any

qrs

where

grd1 : $\mathtt{qrs} \in 50\,..\,150$

grd2 : $\mathtt{qrs} \geq 120$

grd3 : $\mathtt{Sinus} = \mathtt{Yes}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd5 : $\mathtt{Notched\_R}(\mathtt{I}) = \mathtt{TRUE} \land$
$\mathtt{Notched\_R}(\mathtt{V5}) = \mathtt{TRUE} \land$
$\mathtt{Notched\_R}(\mathtt{V6}) = \mathtt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\mathtt{Small\_R\_QS}(\mathtt{V1}) = \mathtt{TRUE} \land$
$\mathtt{Small\_R\_QS}(\mathtt{V2}) = \mathtt{TRUE}$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$

act2 : $\mathtt{Disease\_step2} := \mathtt{LBBB}$

end

Event $QRS\_Test\_RBBB \mathrel{\widehat{=}}$
Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

any

qrs

where

grd1 : $\mathtt{qrs} \in 50\,..\,150$

grd2 : $\mathtt{qrs} \geq 120$

grd3 : $\mathtt{Sinus} = \mathtt{Yes}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd5 : $\mathtt{M\_Shape\_Complex}(\mathtt{V1}) = \mathtt{TRUE} \land$
$\mathtt{M\_Shape\_Complex}(\mathtt{V2}) = \mathtt{TRUE}$

grd7 : $\mathtt{Slurred\_S}(\mathtt{I}) = \mathtt{TRUE} \land$
$\mathtt{Slurred\_S}(\mathtt{V5}) = \mathtt{TRUE} \land$
$\mathtt{Slurred\_S}(\mathtt{V6}) = \mathtt{TRUE}$

grd8 : $\mathtt{Slurred\_S\_duration}(\mathtt{I}) > 40 \land$
$\mathtt{Slurred\_S\_duration}(\mathtt{V5}) > 40 \land$
$\mathtt{Slurred\_S\_duration}(\mathtt{V6}) > 40$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$

act2 : $\mathtt{Disease\_step2} := \mathtt{RBBB}$

end

Event $QRS\_Test\_Atypical\_RLBBB\_WPW\_Syndrome \mathrel{\widehat{=}}$
QRS Test for Atypical LBBB RBBB

extends $QRS\_Test\_Atypical\_RLBBB\_WPW\_Syndrome$

any

sympt

d_wave

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \vee \texttt{sympt} = \texttt{A\_LBBB}$

grd3 : $\texttt{d\_wave} \in \mathbb{N}$

grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$

Delta Wave + PR ≤ 120 Heart_State = KO

grd5 **then**

act2 : $\texttt{Delta\_Wave} := \texttt{d\_wave}$

act3 : $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{Slurred\_S}(\texttt{V5}) = \texttt{FALSE} \wedge$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{FALSE}$

grd5 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$

grd6 : $\texttt{ST\_elevation}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{ST\_elevation}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Sinus} = \texttt{Yes}$

then

act1 : $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$

Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$

grd5 : $\texttt{Epsilon\_Wave}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Epsilon\_Wave}(\texttt{V3}) = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

refines *ST_seg_elevation_Yes*

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $Disease\_step4 \in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$

then

act1 : $Disease\_step4 := STEMI$

end

Event *ST_seg_elevation_NO* $\widehat{=}$
ST segment No....

refines *ST_seg_elevation_No*

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$
$(ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000)$
$\wedge\, l \neq k$

then

act1 : $Disease\_step4 :\in \{Troponin, CK\_MB, Ischemia, Non\_STEMI\}$

end

Event $Acute\_IA\_MI \;\widehat{=}$
Inferior Anterior MI

refines $ST\_seg\_elevation\_Yes$

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

then

act1 : $Disease\_step4 :\in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$

end

END

An Event-B Specification of Step4_ST_MI_Ref2
Generated Date: 25 Nov 2010 @ 03:39:16 PM

MACHINE Step4_ST_MI_Ref2

REFINES Step4_ST_MI_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

`RR_Int_equidistant` RR Interval
`PP_Int_equidistant` PP Interval
`P_Positive` P wave positive or negative
`Sinus` Sinus Rhythm
`Heart_Rate` Heart Rate in BPM
`Heart_State` OK or KO for heart state after ECG Interpretation
`PR_Int` PR Interval
`Disease_step2` At level 2 Disease Codes
`QRS_Int` QRS Interval
`M_Shape_Complex` M-shaped complex in Leads
`Slurred_S` Slurred S wave in Leads
`Notched_R` Notched R wave in Leads
`PP_Interval`
`RR_Interval`
`Small_R_QS` A small R or QS wave in V1 and V2
`Slurred_S_duration` Slurred S duration
`Delta_Wave` Delta Wave
`Disease_step3`
`ST_elevation` ST segment elevation (Coved or Saddle-back)
`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
`ST_seg_ele` ST segment for elevation 1mm=0.1mV
`Disease_step4`
`ST_depression`

INVARIANTS

inv1 : $Sinus = Yes \land Disease\_step4 \in \{Troponin, CK\_MB\} \Rightarrow Heart\_State = KO$
inv2 : $Sinus = Yes \land Disease\_step4 = Non\_STEMI \Rightarrow Heart\_State = KO$
inv3 : $Sinus = Yes \land Disease\_step4 = Ischemia \Rightarrow Heart\_State = KO$

EVENTS

Initialisation
extended

begin
act1 : $\mathtt{RR\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act2 : $\mathtt{PP\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act3 : $\mathtt{P\_Positive} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act4 : $\mathtt{Sinus} := \mathtt{No}$
act5 : $\mathtt{PP\_Interval} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$

act6 : $\texttt{RR\_Interval} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act7 : $\texttt{Heart\_Rate} :\in 1 \,..\, 300$

act8 : $\texttt{Heart\_State} := \texttt{KO}$

act9 : $\texttt{PR\_Int} := 120$

act10 : $\texttt{Disease\_step2} := \texttt{NDS2}$

act11 : $\texttt{QRS\_Int} := 50$

act12 : $\texttt{Notched\_R} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act13 : $\texttt{Small\_R\_QS} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act14 : $\texttt{Slurred\_S\_duration} :\in \texttt{LEADS} \rightarrow \mathbb{N}_1$

act15 : $\texttt{M\_Shape\_Complex} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act16 : $\texttt{Slurred\_S} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act17 : $\texttt{ST\_elevation} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act18 : $\texttt{Epsilon\_Wave} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act19 : $\texttt{Delta\_Wave} := 0$

act20 : $\texttt{Disease\_step3} := \texttt{NDS3}$

act21 : $\texttt{ST\_seg\_ele} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act22 : $\texttt{Disease\_step4} := \texttt{NDS4}$

act57 : $\texttt{ST\_depression} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

end

Event *Rhythm_test_TRUE* $\widehat{=}$

Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l}))$
$\land$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$

grd4 : $\texttt{rate} \in 60 \,..\, 100$

60..100 is the range of normal heart rate

grd5 : $\texttt{PR\_Int} \leq 200$

Heart is Normal if PR ≤ 200 `QRS_Int < 120`

$HeartisNormalifQRS < 120$

grd6grd7 : $\texttt{Disease\_step2} = \texttt{NDS2}$

grd8 : $\texttt{Disease\_step3} = \texttt{NDS3}$

grd9 : $\texttt{Disease\_step4} = \texttt{NDS4}$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{OK}$

end

Event *Rhythm_test_FALSE* $\widehat{=}$

Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $rate \in 1 .. 300$

then

act1 : Sinus := No

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd5 : $rate \in 1 .. 300 \setminus 60 .. 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $Disease\_step3 = WPW\_Syndrome \lor Disease\_step3 = Brugada\_Syndrome \lor$
$Disease\_step3 = RV\_Dysplasia \lor Disease\_step3 = IVCD$

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $pr \in 120 .. 220$

time interval in (ms.)

grd2 : $pr > 200$

grd3 : Sinus = Yes

grd4 : Heart_State = KO

then

act1 : PR_Int := pr

act2 : Disease_step2 := First_degree_AV_Block

end

Event *QRS_Test_LBBB* $\widehat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\mathtt{qrs} \in 50 \,..\, 150$

grd2 : $\mathtt{qrs} \geq 120$

grd3 : $\mathtt{Sinus} = \mathtt{Yes}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd5 : $\mathtt{Notched\_R(I)} = \mathtt{TRUE} \wedge$
$\mathtt{Notched\_R(V5)} = \mathtt{TRUE} \wedge$
$\mathtt{Notched\_R(V6)} = \mathtt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\mathtt{Small\_R\_QS(V1)} = \mathtt{TRUE} \wedge$
$\mathtt{Small\_R\_QS(V2)} = \mathtt{TRUE}$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$

act2 : $\mathtt{Disease\_step2} := \mathtt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\mathtt{qrs} \in 50 \,..\, 150$

grd2 : $\mathtt{qrs} \geq 120$

grd3 : $\mathtt{Sinus} = \mathtt{Yes}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd5 : $\mathtt{M\_Shape\_Complex(V1)} = \mathtt{TRUE} \wedge$
$\mathtt{M\_Shape\_Complex(V2)} = \mathtt{TRUE}$

grd7 : $\mathtt{Slurred\_S(I)} = \mathtt{TRUE} \wedge$
$\mathtt{Slurred\_S(V5)} = \mathtt{TRUE} \wedge$
$\mathtt{Slurred\_S(V6)} = \mathtt{TRUE}$

grd8 : $\mathtt{Slurred\_S\_duration(I)} > 40 \wedge$
$\mathtt{Slurred\_S\_duration(V5)} > 40 \wedge$
$\mathtt{Slurred\_S\_duration(V6)} > 40$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$

act2 : $\mathtt{Disease\_step2} := \mathtt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave

where

grd1 : QRS_Int ≥ 110
grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
grd3 : d_wave ∈ ℕ
grd4 : (d_wave + PR_Int) ≤ 120
Delta Wave + PR ≤ 120 Heart_State = KO
grd5 :

then

act2 : Delta_Wave := d_wave
act3 : Disease_step3 := WPW_Syndrome

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* ≙
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int ≥ 110
grd4 : Slurred_S(V5) = FALSE ∧
Slurred_S(V6) = FALSE
grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
grd6 : ST_elevation(V1) = TRUE ∧
ST_elevation(V2) = TRUE
grd7 : Sinus = Yes

then

act1 : Disease_step3 := Brugada_Syndrome

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* ≙
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int ≥ 110
grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
grd5 : Epsilon_Wave(V1) = TRUE ∧
Epsilon_Wave(V3) = TRUE

then

act1 : $Disease\_step3 := RV\_Dysplasia$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $QRS\_Int \geq 110$

grd2 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, Brugada\_Syndrome, RV\_Dysplasia, NDS3\}$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step3 := IVCD$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

refines *ST_seg_elevation_YES*

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $Disease\_step4 \in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$

then

act1 : $Disease\_step4 := STEMI$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$
Troponin or CK-MB positive YES

refines *ST_seg_elevation_NO*

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$
$(ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000)$
$\wedge\, l \neq k$

grd5 : $Disease\_step4 \in \{Troponin, CK\_MB\}$

then

act1 : $Disease\_step4 := Non\_STEMI$

end

Event $ST\_seg\_elevation\_NO\_TCKMB\_No \mathrel{\widehat{=}}$
Troponin or CK-MB positive No

refines $ST\_seg\_elevation\_NO$

when

grd1 : $Heart\_State = KO$
grd2 : $Sinus = Yes$
grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$
$(ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000)$
$\wedge\, l \neq k$

grd5 : $Disease\_step4 \notin \{Troponin, CK\_MB\}$

then

act1 : $Disease\_step4 := Ischemia$

end

Event $Acute\_IA\_MI \mathrel{\widehat{=}}$
Inferior Anterior MI

refines $Acute\_IA\_MI$

when

grd1 : $Heart\_State = KO$
grd2 : $Sinus = Yes$
grd3 : $\vee$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

then

act1 : $Disease\_step4 :\in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$

end

END

An Event-B Specification of Step5_ctx
Generated Date: 25 Nov 2010 @ 03:38:37 PM

CONTEXT Step5_ctx

SETS

Age_of_Infarct

Disease_Codes_Step5

Mice_State5

CONSTANTS

recent

indeterminate

old

Hypertrophic_cardiomyopathy

lateral_MI

anterior_MI

LVH

emphysema

NDS5

Exclude_Mimics_MI

late_transition

normal_variant

borderline_Qs

NMS

AXIOMS

axm1 : $Age\_of\_Infarct = \{recent, indeterminate, old\}$

axm2 : $\neg recent = indeterminate$

axm3 : $\neg recent = old$

axm4 : $\neg indeterminate = old$

axm5 : $Disease\_Codes\_Step5 = \{Hypertrophic\_cardiomyopathy, lateral\_MI, anterior\_MI, LVH, emphysema, NDS5\}$

axm7 : $\neg Hypertrophic\_cardiomyopathy = lateral\_MI$

axm8 : $\neg Hypertrophic\_cardiomyopathy = anterior\_MI$

axm9 : $\neg Hypertrophic\_cardiomyopathy = LVH$

axm11 : $\neg Hypertrophic\_cardiomyopathy = emphysema$

axm12 : $\neg Hypertrophic\_cardiomyopathy = NDS5$

axm19 : $\neg lateral\_MI = anterior\_MI$

axm20 : $\neg lateral\_MI = LVH$

axm22 : $\neg lateral\_MI = emphysema$

axm23 : $\neg lateral\_MI = NDS5$

axm24 : $\neg anterior\_MI = LVH$

axm26 : $\neg anterior\_MI = emphysema$

axm27 : $\neg anterior\_MI = NDS5$

axm29 : $\neg LVH = emphysema$

axm30 : $\neg LVH = NDS5$

axm33 : $\neg emphysema = NDS5$

axm34 : $Mice\_State5 = \{Exclude\_Mimics\_MI, late\_transition, normal\_variant, borderline\_Qs, NMS\}$

NMS No Mice. State

axm35 : $\neg Exclude\_Mimics\_MI = late\_transition$

axm36 : $\neg Exclude\_Mimics\_MI = normal\_variant$

axm37 : $\neg Exclude\_Mimics\_MI = borderline\_Qs$

axm44 : $\neg Exclude\_Mimics\_MI = NMS$

axm38 : $\neg late\_transition = normal\_variant$

axm39 : $\neg late\_transition = borderline\_Qs$

axm43 : $\neg late\_transition = NMS$

axm40 : $\neg normal\_variant = borderline\_Qs$

axm41 : $\neg normal\_variant = NMS$

axm42 : $\neg borderline\_Qs = NMS$

END

An Event-B Specification of Step5_Q_Waves
Generated Date: 25 Nov 2010 @ 03:39:19 PM

MACHINE Step5_Q_Waves

REFINES Step4_ST_MI_Ref2

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

- `RR_Int_equidistant` RR Interval
- `PP_Int_equidistant` PP Interval
- `P_Positive` P wave positive or negative
- `Sinus` Sinus Rhythm
- `Heart_Rate` Heart Rate in BPM
- `Heart_State` OK or KO for heart state after ECG Interpretation
- `PR_Int` PR Interval
- `Disease_step2` At level 2 Disease Codes
- `QRS_Int` QRS Interval
- `M_Shape_Complex` M-shaped complex in Leads
- `Slurred_S` Slurred S wave in Leads
- `Notched_R` Notched R wave in Leads
- `Small_R_QS` A small R or QS wave in V1 and V2
- `PP_Interval`
- `RR_Interval`
- `Slurred_S_duration` Slurred S duration
- `Delta_Wave` Delta Wave
- `Disease_step3`
- `ST_elevation` ST segment elevation (Coved or Saddle-back)
- `Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
- `ST_seg_ele` ST segment for elevation 1mm=0.1mV
- `Disease_step4`
- `Q_Width` Q wave width
- `Q_Depth` Q wave depth
- `Q_Normal_Status` Q wave normal or abnormal
- `ST_depression`

INVARIANTS

inv1 : $Q\_Width \in LEADS \rightarrow \mathbb{N}$

inv2 : $Q\_Depth \in LEADS \rightarrow \mathbb{N}$

inv3 : $Q\_Normal\_Status \in BOOL$

inv4 : $Sinus = Yes \land Disease\_step4 = Acute\_anterior\_MI$
$\Rightarrow Heart\_State = KO$

inv5 : $Sinus = Yes \land Disease\_step4 = Acute\_inferior\_MI$
$\Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $\texttt{RR\_Int\_equidistant} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act2 : $\texttt{PP\_Int\_equidistant} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act3 : $\texttt{P\_Positive} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act4 : $\texttt{Sinus} := \texttt{No}$

act5 : $\texttt{PP\_Interval} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act6 : $\texttt{RR\_Interval} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act7 : $\texttt{Heart\_Rate} :\in 1 \,..\, 300$

act8 : $\texttt{Heart\_State} := \texttt{KO}$

act9 : $\texttt{PR\_Int} := 120$

act10 : $\texttt{Disease\_step2} := \texttt{NDS2}$

act11 : $\texttt{QRS\_Int} := 50$

act12 : $\texttt{Notched\_R} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act13 : $\texttt{Small\_R\_QS} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act14 : $\texttt{Slurred\_S\_duration} :\in \texttt{LEADS} \rightarrow \mathbb{N}_1$

act15 : $\texttt{M\_Shape\_Complex} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act16 : $\texttt{Slurred\_S} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act17 : $\texttt{ST\_elevation} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act18 : $\texttt{Epsilon\_Wave} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act19 : $\texttt{Delta\_Wave} := 0$

act20 : $\texttt{Disease\_step3} := \texttt{NDS3}$

act21 : $\texttt{ST\_seg\_ele} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act22 : $\texttt{Disease\_step4} := \texttt{NDS4}$

act57 : $\texttt{ST\_depression} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act23 : $Q\_Width :\in LEADS \rightarrow \mathbb{N}$

act24 : $Q\_Depth :\in LEADS \rightarrow \mathbb{N}$

act25 : $Q\_Normal\_Status := FALSE$

end

Event *Rhythm_test_TRUE* $\widehat{=}$

Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l}))$
$\land$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$

grd4 : $\texttt{rate} \in 60 \,..\, 100$

60..100 is the range of normal heart rate

grd5 : $\texttt{PR\_Int} \leq 200$

Heart is Normal if PR $\leq$ 200 `QRS_Int < 120`

$HeartisNormalifQRS < 120$

grd6grd7 : $\texttt{Disease\_step2} = \texttt{NDS2}$

grd8 : $\texttt{Disease\_step3} = \texttt{NDS3}$

grd9 : $\mathtt{Disease\_step4} = \mathtt{NDS4}$

then

act1 : $\mathtt{Sinus} := \mathtt{Yes}$

act2 : $\mathtt{Heart\_Rate} := \mathtt{rate}$

act3 : $\mathtt{Heart\_State} := \mathtt{OK}$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \Rightarrow \mathtt{PP\_Int\_equidistant}(l) = \mathtt{FALSE} \lor \mathtt{RR\_Int\_equidistant}(l) = \mathtt{FALSE} \lor \mathtt{RR\_Interval}(l) \neq \mathtt{PP\_Interval}(l)) \lor \mathtt{P\_Positive}(\mathtt{II}) = \mathtt{FALSE}$

grd2 : $\mathtt{rate} \in 1 \,..\, 300$

then

act1 : $\mathtt{Sinus} := \mathtt{No}$

act2 : $\mathtt{Heart\_Rate} := \mathtt{rate}$

act3 : $\mathtt{Heart\_State} := \mathtt{KO}$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \land \mathtt{PP\_Int\_equidistant}(l) = \mathtt{TRUE} \land \mathtt{RR\_Int\_equidistant}(l) = \mathtt{TRUE} \land \mathtt{RR\_Interval}(l) = \mathtt{PP\_Interval}(l)) \land \mathtt{P\_Positive}(\mathtt{II}) = \mathtt{TRUE}$

grd5 : $\mathtt{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $\mathtt{Disease\_step3} = \mathtt{WPW\_Syndrome} \lor \mathtt{Disease\_step3} = \mathtt{Brugada\_Syndrome} \lor \mathtt{Disease\_step3} = \mathtt{RV\_Dysplasia} \lor \mathtt{Disease\_step3} = \mathtt{IVCD}$

then

act1 : $\mathtt{Sinus} := \mathtt{Yes}$

act2 : $\mathtt{Heart\_Rate} := \mathtt{rate}$

act3 : $\mathtt{Heart\_State} := \mathtt{KO}$

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\texttt{pr} \in 120 \,..\, 220$
time interval in (ms.)

grd2 : $\texttt{pr} > 200$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{PR\_Int} := \texttt{pr}$

act2 : $\texttt{Disease\_step2} := \texttt{First\_degree\_AV\_Block}$

end

Event *QRS_Test_LBBB* $\widehat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{Notched\_R}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V6}) = \texttt{TRUE}$
Right Bundle Branch Block (RBBB)

grd6 : $\texttt{Small\_R\_QS}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Small\_R\_QS}(\texttt{V2}) = \texttt{TRUE}$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{M\_Shape\_Complex}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{TRUE}$

grd8 : $\mathtt{Slurred\_S\_duration(I)} > 40 \land$
$\mathtt{Slurred\_S\_duration(V5)} > 40 \land$
$\mathtt{Slurred\_S\_duration(V6)} > 40$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$

act2 : $\mathtt{Disease\_step2} := \mathtt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt

d_wave

where

grd1 : $\mathtt{QRS\_Int} \geq 110$

grd2 : $\mathtt{sympt} = \mathtt{A\_RBBB} \lor \mathtt{sympt} = \mathtt{A\_LBBB}$

grd3 : $\mathtt{d\_wave} \in \mathbb{N}$

grd4 : $(\mathtt{d\_wave} + \mathtt{PR\_Int}) \leq 120$
Delta Wave + PR ≤ 120 Heart_State = KO

grd5 **then**

act2 : $\mathtt{Delta\_Wave} := \mathtt{d\_wave}$

act3 : $\mathtt{Disease\_step3} := \mathtt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt

dis

where

grd1 : $\mathtt{sympt} = \mathtt{A\_RBBB}$

grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd3 : $\mathtt{QRS\_Int} \geq 110$

grd4 : $\mathtt{Slurred\_S(V5)} = \mathtt{FALSE} \land$
$\mathtt{Slurred\_S(V6)} = \mathtt{FALSE}$

grd5 : $\mathtt{dis} \in \mathtt{Disease\_Codes\_Step3} \setminus \{\mathtt{WPW\_Syndrome}, \mathtt{NDS3}\}$

grd6 : $\mathtt{ST\_elevation(V1)} = \mathtt{TRUE} \land$
$\mathtt{ST\_elevation(V2)} = \mathtt{TRUE}$

grd7 : $\mathtt{Sinus} = \mathtt{Yes}$

then

act1 : $\mathtt{Disease\_step3} := \mathtt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$
grd2 : $\texttt{Heart\_State} = \texttt{KO}$
grd3 : $\texttt{QRS\_Int} \geq 110$
grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$
grd5 : $\texttt{Epsilon\_Wave(V1)} = \texttt{TRUE} \land$ $\texttt{Epsilon\_Wave(V3)} = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$
grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$
grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

refines *ST_seg_elevation_YES*

when

grd1 : $Heart\_State = KO$
grd2 : $Sinus = Yes$
grd3 : $\lor$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$
$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$
$\land$
$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$
$\land\, l1 \neq k1$
$\land$
$($
$(l1 = V1 \land k1 = V2) \lor$
$(l1 = V2 \land k1 = V3) \lor$
$(l1 = V3 \land k1 = V4) \lor$
$(l1 = V4 \land k1 = V5) \lor$
$(l1 = V5 \land k1 = V6)$
$)$
$))$

grd4 : $Disease\_step4 \in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$

then

act1 : $Disease\_step4 := STEMI$

end

Event $ST\_seg\_elevation\_NOTCKMB\_Yes \triangleq$
Troponin or CK-MB positive YES

extends $ST\_seg\_elevation\_NOTCKMB\_Yes$

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd2 : $\mathtt{Sinus} = \mathtt{Yes}$
grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$
grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression(l)} \geq 1000 \wedge \mathtt{ST\_depression(k)} \geq 1000)$
$\wedge\, \mathtt{l} \neq \mathtt{k}$
grd5 : $\mathtt{Disease\_step4} \in \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Non\_STEMI}$

end

Event $ST\_seg\_elevation\_NO\_TCKMB\_No \triangleq$
Troponin or CK-MB positive No

extends $ST\_seg\_elevation\_NO\_TCKMB\_No$

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd2 : $\mathtt{Sinus} = \mathtt{Yes}$
grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$
grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression(l)} \geq 1000 \wedge \mathtt{ST\_depression(k)} \geq 1000)$
$\wedge\, \mathtt{l} \neq \mathtt{k}$
grd5 : $\mathtt{Disease\_step4} \notin \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Ischemia}$

end

Event $Q\_Assessment\_Normal \triangleq$
Q wave assessment normal

when

grd1 : $Q\_Width(II) < 40 \wedge Q\_Depth(II) \leq 3000 \wedge$
$Q\_Width(aVF) < 40 \wedge Q\_Depth(aVF) \leq 3000 \wedge$
$Q\_Width(aVL) < 40$
1000 micrometer= 1 milimeter
grd2 : $Q\_Width(III) \leq 40 \wedge Q\_Depth(III) \leq 7000 \wedge Q\_Depth(aVL) \leq 7000$
grd3 : $Q\_Depth(I) < 40 \wedge Q\_Depth(I) \leq 1500$

then

act1 : $Q\_Normal\_Status := TRUE$

end

Event $Q\_Assessment\_Abnormal\_AMI \widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

refines $Acute\_IA\_MI$

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $Q\_Width(V5) \geq 40 \wedge Q\_Depth(V5) > 3000 \wedge$
$Q\_Width(V6) \geq 40 \wedge Q\_Depth(V6) > 3000$

grd5 : $Q\_Width(aVL) \geq 40 \wedge Q\_Depth(aVL) > 7000$

grd6 : $Q\_Depth(I) \geq 40 \wedge Q\_Depth(I) > 1500$

grd7 : $Q\_Normal\_Status = FALSE$

then

act1 : $Disease\_step4 := Acute\_anterior\_MI$

end

Event $Q\_Assessment\_Abnormal\_IMI \widehat{=}$
Q wave assessment abnormal for inferior MI (IMI)

refines $Acute\_IA\_MI$

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $Q\_Width(II) \geq 40 \wedge Q\_Depth(II) > 3000 \wedge$
$Q\_Width(III) > 40 \wedge Q\_Depth(III) > 7000 \wedge$
$Q\_Width(aVF) \geq 40 \wedge Q\_Depth(aVF) > 3000$

grd5 : $Q\_Normal\_Status = FALSE$

then

act1 : $Disease\_step4 := Acute\_inferior\_MI$

end

END

An Event-B Specification of Step5_Q_Waves_Ref1
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MACHINE Step5_Q_Waves_Ref1

REFINES Step5_Q_Waves

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx

VARIABLES

`RR_Int_equidistant` RR Interval
`PP_Int_equidistant` PP Interval
`P_Positive` P wave positive or negative
`Sinus` Sinus Rhythm
`Heart_Rate` Heart Rate in BPM
`Heart_State` OK or KO for heart state after ECG Interpretation
`PR_Int` PR Interval
`Disease_step2` At level 2 Disease Codes
`QRS_Int` QRS Interval
`M_Shape_Complex` M-shaped complex in Leads
`Slurred_S` Slurred S wave in Leads
`Notched_R` Notched R wave in Leads
`Small_R_QS` A small R or QS wave in V1 and V2
`Slurred_S_duration` Slurred S duration
`Delta_Wave` Delta Wave
`Disease_step3`
`ST_elevation` ST segment elevation (Coved or Saddle-back)
`PP_Interval`
`RR_Interval`
`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
`ST_seg_ele` ST segment for elevation 1mm=0.1mV
`Disease_step4`
`Q_Width` Q wave width
`Q_Depth` Q wave depth
`Q_Normal_Status` Q wave normal or abnormal
`Age_of_Inf` Age of Infarct
`Disease_step5`
`Mice_State`
`R_Depth` R wave depth or height
`R_Normal_Status` R wave normal or abnormal
`Q_Wave_State` Q wave states for all LEADS
`ST_depression`

INVARIANTS

inv1 : $Age\_of\_Inf \in Age\_of\_Infarct$
inv2 : $Disease\_step5 \in Disease\_Codes\_Step5$
inv3 : $Mice\_State \in Mice\_State5$

inv4 : $R\_Depth \in LEADS \to \mathbb{N}$

inv5 : $R\_Normal\_Status \in BOOL$

inv6 : $Q\_Wave\_State \in LEADS \to BOOL$

inv7 : $Sinus = Yes \land Disease\_step5 = Hypertrophic\_cardiomyopathy \Rightarrow Heart\_State = KO$

inv8 : $Sinus = Yes \land Disease\_step5 \in \{anterior\_MI, LVH, emphysema, lateral\_MI\} \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $\mathtt{RR\_Int\_equidistant} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act2 : $\mathtt{PP\_Int\_equidistant} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act3 : $\mathtt{P\_Positive} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act4 : $\mathtt{Sinus} := \mathtt{No}$

act5 : $\mathtt{PP\_Interval} :\in \mathtt{LEADS} \to \mathbb{N}$

act6 : $\mathtt{RR\_Interval} :\in \mathtt{LEADS} \to \mathbb{N}$

act7 : $\mathtt{Heart\_Rate} :\in 1 \mathinner{..} 300$

act8 : $\mathtt{Heart\_State} := \mathtt{KO}$

act9 : $\mathtt{PR\_Int} := 120$

act10 : $\mathtt{Disease\_step2} := \mathtt{NDS2}$

act11 : $\mathtt{QRS\_Int} := 50$

act12 : $\mathtt{Notched\_R} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act13 : $\mathtt{Small\_R\_QS} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act14 : $\mathtt{Slurred\_S\_duration} :\in \mathtt{LEADS} \to \mathbb{N}_1$

act15 : $\mathtt{M\_Shape\_Complex} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act16 : $\mathtt{Slurred\_S} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act17 : $\mathtt{ST\_elevation} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act18 : $\mathtt{Epsilon\_Wave} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act19 : $\mathtt{Delta\_Wave} := 0$

act20 : $\mathtt{Disease\_step3} := \mathtt{NDS3}$

act21 : $\mathtt{ST\_seg\_ele} :\in \mathtt{LEADS} \to \mathbb{N}$

act22 : $\mathtt{Disease\_step4} := \mathtt{NDS4}$

act57 : $\mathtt{ST\_depression} :\in \mathtt{LEADS} \to \mathbb{N}$

act23 : $\mathtt{Q\_Width} :\in \mathtt{LEADS} \to \mathbb{N}$

act24 : $\mathtt{Q\_Depth} :\in \mathtt{LEADS} \to \mathbb{N}$

act25 : $\mathtt{Q\_Normal\_Status} := \mathtt{FALSE}$

act26 : $Mice\_State := NMS$

act27 : $R\_Depth :\in LEADS \to \mathbb{N}$

act28 : $R\_Normal\_Status := FALSE$

act29 : $Q\_Wave\_State :\in LEADS \to BOOL$

act30 : $Age\_of\_Inf :\in Age\_of\_Infarct$

act31 : $Disease\_step5 := NDS5$

end

Event $Rhythm\_test\_TRUE \mathrel{\widehat{=}}$

Sinus Rhythm with Normal Rate

extends $Rhythm\_test\_TRUE$

any

rate

where

grd1 : $(\exists \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \land \mathtt{PP\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \land$
$\mathtt{RR\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \land$
$\mathtt{RR\_Interval}(\mathtt{l}) = \mathtt{PP\_Interval}(\mathtt{l}))$
$\land$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{TRUE}$

grd4 : $\mathtt{rate} \in 60 .. 100$

60..100 is the range of normal heart rate

grd5 : $\mathtt{PR\_Int} \leq 200$

Heart is Normal if PR ≤ 200 QRS_Int < 120

$Heart is Normal if QRS < 120$

grd6grd7 : $\mathtt{Disease\_step2} = \mathtt{NDS2}$

grd8 : $\mathtt{Disease\_step3} = \mathtt{NDS3}$

grd9 : $\mathtt{Disease\_step4} = \mathtt{NDS4}$

grd10 : $Disease\_step5 = NDS5$

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := OK

end

Event *Rhythm_test_FALSE* $\widehat{=}$

Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \Rightarrow \mathtt{PP\_Int\_equidistant}(\mathtt{l}) = \mathtt{FALSE} \lor$
$\mathtt{RR\_Int\_equidistant}(\mathtt{l}) = \mathtt{FALSE} \lor$
$\mathtt{RR\_Interval}(\mathtt{l}) \neq \mathtt{PP\_Interval}(\mathtt{l}))$
$\lor$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{FALSE}$

grd2 : $\mathtt{rate} \in 1 .. 300$

then

act1 : Sinus := No

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \land \mathtt{PP\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \land$
$\mathtt{RR\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \land$
$\mathtt{RR\_Interval}(\mathtt{l}) = \mathtt{PP\_Interval}(\mathtt{l}))$
$\land$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{TRUE}$

grd5 : $rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal
grd6 : $Disease\_step3 = WPW\_Syndrome \lor Disease\_step3 = Brugada\_Syndrome \lor Disease\_step3 = RV\_Dysplasia \lor Disease\_step3 = IVCD$

then

act1 : $Sinus := Yes$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := KO$

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $pr \in 120 \,..\, 220$
time interval in (ms.)
grd2 : $pr > 200$
grd3 : $Sinus = Yes$
grd4 : $Heart\_State = KO$

then

act1 : $PR\_Int := pr$
act2 : $Disease\_step2 := First\_degree\_AV\_Block$

end

Event *QRS_Test_LBBB* $\widehat{=}$
QRS Complex Interval Test

refines *QRS_Test_LBBB*

any

qrs

where

grd1 : $qrs \in 50 \,..\, 150$
grd2 : $qrs \geq 120$
grd3 : $Sinus = Yes$
grd4 : $Heart\_State = KO$
grd5 : $Notched\_R(I) = TRUE \land Notched\_R(V5) = TRUE \land Notched\_R(V6) = TRUE$
Right Bundle Branch Block (RBBB)
grd6 : $Small\_R\_QS(V1) = TRUE \land Small\_R\_QS(V2) = TRUE$
grd7 : $Q\_Wave\_State(V1) = TRUE \land Q\_Wave\_State(V2) = TRUE \land Q\_Wave\_State(V3) = TRUE \land Q\_Wave\_State(V4) = TRUE$
from step 5
grd8 : $R\_Normal\_Status = FALSE$
from step 5

then

act1 : $QRS\_Int := qrs$

act2 : $Disease\_step2 := LBBB$

end

Event $QRS\_Test\_RBBB \mathrel{\widehat{=}}$

Right Bundle Branch Block (RBBB)

refines QRS_Test_RBBB

any

qrs

where

grd1 : $qrs \in 50 \,..\, 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $M\_Shape\_Complex(V1) = TRUE \land M\_Shape\_Complex(V2) = TRUE$

grd7 : $Slurred\_S(I) = TRUE \land Slurred\_S(V5) = TRUE \land Slurred\_S(V6) = TRUE$

grd8 : $Slurred\_S\_duration(I) > 40 \land Slurred\_S\_duration(V5) > 40 \land Slurred\_S\_duration(V6) > 40$

then

act1 : $QRS\_Int := qrs$

act2 : $Disease\_step2 := RBBB$

end

Event $QRS\_Test\_Atypical\_RLBBB\_WPW\_Syndrome \mathrel{\widehat{=}}$

QRS Test for Atypical LBBB RBBB

refines $QRS\_Test\_Atypical\_RLBBB\_WPW\_Syndrome$

any

$sympt$

d_wave

$exmi$

where

grd1 : $QRS\_Int \geq 110$

grd2 : $sympt = A\_RBBB \lor sympt = A\_LBBB$

grd3 : $d\_wave \in \mathbb{N}$

grd4 : $(d\_wave + PR\_Int) \leq 120$

Delta Wave + PR ≤ 120 $Heart\_State = KO$

grd5grd6 : $Disease\_step4 = Acute\_inferior\_MI$

grd7 : $exmi \in Mice\_State5 \land exmi = Exclude\_Mimics\_MI$

then

act2 : $Delta\_Wave := d\_wave$

act3 : $Disease\_step3 := WPW\_Syndrome$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int $\geq$ 110
grd4 : Slurred_S(V5) = FALSE $\wedge$
Slurred_S(V6) = FALSE
grd5 : dis $\in$ Disease_Codes_Step3 $\setminus$ {WPW_Syndrome, NDS3}
grd6 : ST_elevation(V1) = TRUE $\wedge$
ST_elevation(V2) = TRUE
grd7 : Sinus = Yes

then

act1 : Disease_step3 := Brugada_Syndrome

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int $\geq$ 110
grd4 : dis $\in$ Disease_Codes_Step3 $\setminus$ {WPW_Syndrome, Brugada_Syndrome, NDS3}
grd5 : Epsilon_Wave(V1) = TRUE $\wedge$
Epsilon_Wave(V3) = TRUE

then

act1 : Disease_step3 := RV_Dysplasia

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : QRS_Int $\geq$ 110
grd2 : dis $\in$ Disease_Codes_Step3 $\setminus$ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
grd3 : Heart_State = KO

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$

ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge (ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE) \wedge (ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000) \wedge l1 \neq k1 \wedge ((l1 = V1 \wedge k1 = V2) \vee (l1 = V2 \wedge k1 = V3) \vee (l1 = V3 \wedge k1 = V4) \vee (l1 = V4 \wedge k1 = V5) \vee (l1 = V5 \wedge k1 = V6))))$$

grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$

Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow (ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge (\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000) \wedge \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \in \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$

Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

$\texttt{grd1} : \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd2} : \texttt{Sinus} = \texttt{Yes}$

$\texttt{grd3} :$ $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

$\texttt{grd4} : \exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge\, \texttt{l} \neq \texttt{k}$

$\texttt{grd5} : \texttt{Disease\_step4} \notin \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

$\texttt{act1} : \texttt{Disease\_step4} := \texttt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

$\texttt{grd1} : \texttt{Q\_Width}(\texttt{II}) < 40 \wedge \texttt{Q\_Depth}(\texttt{II}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVF}) < 40 \wedge \texttt{Q\_Depth}(\texttt{aVF}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVL}) < 40$

1000 micrometer= 1 milimeter

$\texttt{grd2} : \texttt{Q\_Width}(\texttt{III}) \leq 40 \wedge \texttt{Q\_Depth}(\texttt{III}) \leq 7000 \wedge \texttt{Q\_Depth}(\texttt{aVL}) \leq 7000$

$\texttt{grd3} : \texttt{Q\_Depth}(\texttt{I}) < 40 \wedge \texttt{Q\_Depth}(\texttt{I}) \leq 1500$

then

$\texttt{act1} : \texttt{Q\_Normal\_Status} := \texttt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

$\texttt{grd1} : \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd2} : \texttt{Sinus} = \texttt{Yes}$

$\texttt{grd3} :$ $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

$\texttt{grd4} : \texttt{Q\_Width}(\texttt{V5}) \geq 40 \wedge \texttt{Q\_Depth}(\texttt{V5}) > 3000 \wedge$
$\texttt{Q\_Width}(\texttt{V6}) \geq 40 \wedge \texttt{Q\_Depth}(\texttt{V6}) > 3000$

$\texttt{grd5} : \texttt{Q\_Width}(\texttt{aVL}) \geq 40 \wedge \texttt{Q\_Depth}(\texttt{aVL}) > 7000$

grd6 : $\texttt{Q\_Depth(I)} \geq 40 \land \texttt{Q\_Depth(I)} > 1500$
grd7 : $\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Acute\_anterior\_MI}$

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$
Q wave assessment abnormal for inferior MI (IMI)

refines *Q_Assessment_Abnormal_IMI*

when

grd1 : $Heart\_State = KO$
grd2 : $Sinus = Yes$
grd3 : $\lor$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$
$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$
$\land$
$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$
$\land l1 \neq k1$
$\land$
$($
$(l1 = V1 \land k1 = V2) \lor$
$(l1 = V2 \land k1 = V3) \lor$
$(l1 = V3 \land k1 = V4) \lor$
$(l1 = V4 \land k1 = V5) \lor$
$(l1 = V5 \land k1 = V6)$
$)$
$))$

grd4 : $Q\_Width(II) \geq 40 \land Q\_Depth(II) > 3000 \land$
$Q\_Width(III) > 40 \land Q\_Depth(III) > 7000 \land$
$Q\_Width(aVF) \geq 40 \land Q\_Depth(aVF) > 3000$
grd5 : $Q\_Normal\_Status = FALSE$

then

act1 : $Disease\_step4 := Acute\_inferior\_MI$

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

when

grd1 : $Disease\_step4 = Acute\_inferior\_MI$
$\lor$
$Disease\_step5 \in \{anterior\_MI, LVH, emphysema\}$
$\lor$
$Mice\_State = Exclude\_Mimics\_MI$
$\lor$
$Disease\_step2 = LBBB$

then

act1 : $Age\_of\_Inf :\in \{recent, old, indeterminate\}$

end

Event *Exclude_Mimics* $\widehat{=}$

any

exmi

where

grd1 : $Disease\_step4 = Acute\_inferior\_MI$

grd2 : $exmi \in Mice\_State5 \wedge exmi = Exclude\_Mimics\_MI$

then

act1 : $Disease\_step5 := Hypertrophic\_cardiomyopathy$

act2 : $Mice\_State := borderline\_Qs$

end

Event $R\_Assessment\_Normal \ \widehat{=}$

Q wave assessment normal

any

age

where

grd1 : $R\_Depth(V1) \geq 0 \wedge R\_Depth(V1) \leq 6000 \wedge age > 30$

1000 micrometer= 1 milimeter

grd2 : $R\_Depth(V2) > 200 \wedge R\_Depth(V2) \leq 12000$

grd3 : $R\_Depth(V2) \geq 1000 \wedge R\_Depth(V2) \leq 24000$

then

act1 : $R\_Normal\_Status := TRUE$

end

Event $R\_Assessment\_Abnormal \ \widehat{=}$

when

grd1 : $R\_Normal\_Status = FALSE$

then

act1 : $Mice\_State :\in \{late\_transition, normal\_variant\}$

end

Event $R\_Q\_Assessment\_R\_Abnormal\_V1234 \ \widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

when

grd1 : $R\_Normal\_Status = FALSE$

grd2 : $Q\_Wave\_State(V1) = TRUE \wedge$
$Q\_Wave\_State(V2) = TRUE \wedge$
$Q\_Wave\_State(V3) = TRUE \wedge$
$Q\_Wave\_State(V4) = TRUE$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step5 :\in \{anterior\_MI, LVH, emphysema\}$

act2 : $Mice\_State := Exclude\_Mimics\_MI$

end

Event $R\_Q\_Assessment\_R\_Abnormal\_V56 \ \widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

when

grd1 : $Q\_Wave\_State(V5) = TRUE \wedge$
$Q\_Wave\_State(V6) = TRUE$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step5 :\in \{lateral\_MI, Hypertrophic\_cardiomyopathy\}$

end

END

An Event-B Specification of Step6_ctx
Generated Date: 25 Nov 2010 @ 03:38:56 PM

CONTEXT Step6_ctx

SETS

`Disease_Codes_Step6`

CONSTANTS

`RAE` Right Atrial Enlargement

`RVH`

`RV_strain`

`pulmonary_embolism`

`LAE` Left Atrial Enlargement

`mitral_stenosis`

`mitral_regurgitation`

`LV_failure`

`dilated_cardiomyopathy`

`LVH_cause`

`NDS6`

AXIOMS

axm1 : $Disease\_Codes\_Step6 = \{RAE, RVH, RV\_strain, pulmonary\_embolism, LAE, mitral\_stenosis, mitral\_regurgitation, LV\_failure, dilated\_cardiomyopathy, LVH\_cause, NDS6\}$

axm2 : $\neg RAE = RVH$

axm3 : $\neg RAE = RV\_strain$

axm4 : $\neg RAE = pulmonary\_embolism$

axm5 : $\neg RAE = LAE$

axm6 : $\neg RAE = mitral\_stenosis$

axm7 : $\neg RAE = mitral\_regurgitation$

axm8 : $\neg RAE = LV\_failure$

axm9 : $\neg RAE = dilated\_cardiomyopathy$

axm10 : $\neg RAE = LVH\_cause$

axm11 : $\neg RAE = NDS6$

axm12 : $\neg RVH = RV\_strain$

axm13 : $\neg RVH = pulmonary\_embolism$

axm14 : $\neg RVH = LAE$

axm15 : $\neg RVH = mitral\_stenosis$

axm16 : $\neg RVH = mitral\_regurgitation$

axm17 : $\neg RVH = LV\_failure$

axm18 : $\neg RVH = dilated\_cardiomyopathy$

axm19 : $\neg RVH = LVH\_cause$

axm20 : $\neg RVH = NDS6$

axm21 : $\neg RV\_strain = pulmonary\_embolism$

axm22 : $\neg RV\_strain = LAE$

axm23 : $\neg RV\_strain = mitral\_stenosis$

$\texttt{axm24}: \neg RV\_strain = mitral\_regurgitation$

$\texttt{axm25}: \neg RV\_strain = LV\_failure$

$\texttt{axm26}: \neg RV\_strain = dilated\_cardiomyopathy$

$\texttt{axm27}: \neg RV\_strain = LVH\_cause$

$\texttt{axm28}: \neg RV\_strain = NDS6$

$\texttt{axm29}: \neg pulmonary\_embolism = LAE$

$\texttt{axm30}: \neg pulmonary\_embolism = mitral\_stenosis$

$\texttt{axm31}: \neg pulmonary\_embolism = mitral\_regurgitation$

$\texttt{axm32}: \neg pulmonary\_embolism = LV\_failure$

$\texttt{axm33}: \neg pulmonary\_embolism = dilated\_cardiomyopathy$

$\texttt{axm34}: \neg pulmonary\_embolism = LVH\_cause$

$\texttt{axm35}: \neg pulmonary\_embolism = NDS6$

$\texttt{axm36}: \neg LAE = mitral\_stenosis$

$\texttt{axm37}: \neg LAE = mitral\_regurgitation$

$\texttt{axm38}: \neg LAE = LV\_failure$

$\texttt{axm39}: \neg LAE = dilated\_cardiomyopathy$

$\texttt{axm40}: \neg LAE = LVH\_cause$

$\texttt{axm41}: \neg LAE = NDS6$

$\texttt{axm42}: \neg mitral\_stenosis = mitral\_regurgitation$

$\texttt{axm43}: \neg mitral\_stenosis = LV\_failure$

$\texttt{axm44}: \neg mitral\_stenosis = dilated\_cardiomyopathy$

$\texttt{axm45}: \neg mitral\_stenosis = LVH\_cause$

$\texttt{axm46}: \neg mitral\_stenosis = NDS6$

$\texttt{axm47}: \neg mitral\_regurgitation = LV\_failure$

$\texttt{axm48}: \neg mitral\_regurgitation = dilated\_cardiomyopathy$

$\texttt{axm49}: \neg mitral\_regurgitation = LVH\_cause$

$\texttt{axm50}: \neg mitral\_regurgitation = NDS6$

$\texttt{axm51}: \neg LV\_failure = dilated\_cardiomyopathy$

$\texttt{axm52}: \neg LV\_failure = LVH\_cause$

$\texttt{axm53}: \neg LV\_failure = NDS6$

$\texttt{axm54}: \neg dilated\_cardiomyopathy = LVH\_cause$

$\texttt{axm55}: \neg dilated\_cardiomyopathy = NDS6$

$\texttt{axm56}: \neg LVH\_cause = NDS6$

END

An Event-B Specification of Step6_P_Wave
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MACHINE Step6_P_Wave

REFINES Step5_Q_Waves_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx

VARIABLES

- `RR_Int_equidistant` RR Interval
- `PP_Int_equidistant` PP Interval
- `P_Positive` P wave positive or negative
- `Sinus` Sinus Rhythm
- `Heart_Rate` Heart Rate in BPM
- `Heart_State` OK or KO for heart state after ECG Interpretation
- `PR_Int` PR Interval
- `Disease_step2` At level 2 Disease Codes
- `QRS_Int` QRS Interval
- `M_Shape_Complex` M-shaped complex in Leads
- `Slurred_S` Slurred S wave in Leads
- `Notched_R` Notched R wave in Leads
- `Small_R_QS` A small R or QS wave in V1 and V2
- `Slurred_S_duration` Slurred S duration
- `Delta_Wave` Delta Wave
- `Disease_step3`
- `ST_elevation` ST segment elevation (Coved or Saddle-back)
- `PP_Interval`
- `RR_Interval`
- `Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
- `ST_seg_ele` ST segment for elevation 1mm=0.1mV
- `Disease_step4`
- `Q_Width` Q wave width
- `Q_Depth` Q wave depth
- `Q_Normal_Status` Q wave normal or abnormal
- `Age_of_Inf` Age of Infarct
- `Disease_step5`
- `Mice_State`
- `R_Depth` R wave depth or height
- `R_Normal_Status` R wave normal or abnormal
- `Q_Wave_State` Q wave states for all LEADS
- `P_Wave_Peak` function to estimate the peak of LEADS signal
- `Disease_step6`
- `Diphasic`
- `P_Wave_Broad`
- `ST_depression`

INVARIANTS

inv1 : $P\_Wave\_Peak \in LEADS \rightarrow \mathbb{N}$

inv2 : $Disease\_step6 \in Disease\_Codes\_Step6$

inv3 : $Diphasic \in LEADS \rightarrow BOOL$

inv4 : $P\_Wave\_Broad \in LEADS \rightarrow \mathbb{N}$

inv5 : $Sinus = Yes \land Disease\_step6 \in \{RAE, RVH, RV\_strain, pulmonary\_embolism, LAE, mitral\_stenosis, mitral\_regurgitation, LV\_failure, dilated\_cardiomyopathy, LVH\_cause\} \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : RR_Int_equidistant $:\in$ LEADS $\rightarrow$ BOOL
act2 : PP_Int_equidistant $:\in$ LEADS $\rightarrow$ BOOL
act3 : P_Positive $:\in$ LEADS $\rightarrow$ BOOL
act4 : Sinus $:=$ No
act5 : PP_Interval $:\in$ LEADS $\rightarrow \mathbb{N}$
act6 : RR_Interval $:\in$ LEADS $\rightarrow \mathbb{N}$
act7 : Heart_Rate $:\in 1 .. 300$
act8 : Heart_State $:=$ KO
act9 : PR_Int $:= 120$
act10 : Disease_step2 $:=$ NDS2
act11 : QRS_Int $:= 50$
act12 : Notched_R $:\in$ LEADS $\rightarrow$ BOOL
act13 : Small_R_QS $:\in$ LEADS $\rightarrow$ BOOL
act14 : Slurred_S_duration $:\in$ LEADS $\rightarrow \mathbb{N}_1$
act15 : M_Shape_Complex $:\in$ LEADS $\rightarrow$ BOOL
act16 : Slurred_S $:\in$ LEADS $\rightarrow$ BOOL
act17 : ST_elevation $:\in$ LEADS $\rightarrow$ BOOL
act18 : Epsilon_Wave $:\in$ LEADS $\rightarrow$ BOOL
act19 : Delta_Wave $:= 0$
act20 : Disease_step3 $:=$ NDS3
act21 : ST_seg_ele $:\in$ LEADS $\rightarrow \mathbb{N}$
act22 : Disease_step4 $:=$ NDS4
act57 : ST_depression $:\in$ LEADS $\rightarrow \mathbb{N}$
act23 : Q_Width $:\in$ LEADS $\rightarrow \mathbb{N}$
act24 : Q_Depth $:\in$ LEADS $\rightarrow \mathbb{N}$
act25 : Q_Normal_Status $:=$ FALSE
act26 : Mice_State $:=$ NMS
act27 : R_Depth $:\in$ LEADS $\rightarrow \mathbb{N}$
act28 : R_Normal_Status $:=$ FALSE
act29 : Q_Wave_State $:\in$ LEADS $\rightarrow$ BOOL
act30 : Age_of_Inf $:\in$ Age_of_Infarct
act31 : Disease_step5 $:=$ NDS5
act32 : $Diphasic :\in LEADS \rightarrow BOOL$
act33 : $P\_Wave\_Broad :\in LEADS \rightarrow \mathbb{N}$
act34 : $P\_Wave\_Peak :\in LEADS \rightarrow \mathbb{N}$
act35 : $Disease\_step6 := NDS6$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land RR\_Int\_equidistant(l) = TRUE \land RR\_Interval(l) = PP\_Interval(l)) \land P\_Positive(II) = TRUE$

grd4 : $rate \in 60 .. 100$
60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$
Heart is Normal if PR $\leq$ 200 QRS_Int < 120
$HeartisNormalifQRS < 120$

grd6grd7 : $Disease\_step2 = NDS2$

grd8 : $Disease\_step3 = NDS3$

grd9 : $Disease\_step4 = NDS4$

grd10 : $Disease\_step5 = NDS5$

grd11 : $Disease\_step6 = NDS6$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor RR\_Int\_equidistant(l) = FALSE \lor RR\_Interval(l) \neq PP\_Interval(l)) \lor P\_Positive(II) = FALSE$

grd2 : $rate \in 1 .. 300$

then

act1 : $Sinus := No$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \wedge \text{PP\_Int\_equidistant}(l) = \text{TRUE} \wedge$
$\text{RR\_Int\_equidistant}(l) = \text{TRUE} \wedge$
$\text{RR\_Interval}(l) = \text{PP\_Interval}(l))$
$\wedge$
$\text{P\_Positive}(II) = \text{TRUE}$

grd5 : $\text{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $\text{Disease\_step3} = \text{WPW\_Syndrome} \vee \text{Disease\_step3} = \text{Brugada\_Syndrome} \vee$
$\text{Disease\_step3} = \text{RV\_Dysplasia} \vee \text{Disease\_step3} = \text{IVCD}$

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\text{pr} \in 120 \,..\, 220$

time interval in (ms.)

grd2 : $\text{pr} > 200$

grd3 : Sinus = Yes

grd4 : Heart_State = KO

then

act1 : PR_Int := pr

act2 : Disease_step2 := First_degree_AV_Block

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\text{qrs} \in 50 \,..\, 150$

grd2 : $\text{qrs} \geq 120$

grd3 : Sinus = Yes

grd4 : Heart_State = KO

grd5 : $\text{Notched\_R}(I) = \text{TRUE} \wedge$
$\text{Notched\_R}(V5) = \text{TRUE} \wedge$
$\text{Notched\_R}(V6) = \text{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\texttt{Small\_R\_QS(V1)} = \texttt{TRUE} \wedge$
$\texttt{Small\_R\_QS(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Q\_Wave\_State(V1)} = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State(V2)} = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State(V3)} = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State(V4)} = \texttt{TRUE}$

from step 5

grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

from step 5

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$

Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \mathinner{..} 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex(V1)} = \texttt{TRUE} \wedge$
$\texttt{M\_Shape\_Complex(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S(I)} = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S(V5)} = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S(V6)} = \texttt{TRUE}$

grd8 : $\texttt{Slurred\_S\_duration(I)} > 40 \wedge$
$\texttt{Slurred\_S\_duration(V5)} > 40 \wedge$
$\texttt{Slurred\_S\_duration(V6)} > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$

QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt

d_wave

exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \vee \texttt{sympt} = \texttt{A\_LBBB}$

grd3 : $\texttt{d\_wave} \in \mathbb{N}$

grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$

Delta Wave + PR $\leq$ 120 `Heart_State = KO`

grd5grd6 : Disease_step4 = Acute_inferior_MI
grd7 : exmi $\in$ Mice_State5 $\wedge$ exmi = Exclude_Mimics_MI

then

act2 : Delta_Wave := d_wave
act3 : Disease_step3 := WPW_Syndrome

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int $\geq$ 110
grd4 : Slurred_S(V5) = FALSE $\wedge$
Slurred_S(V6) = FALSE
grd5 : dis $\in$ Disease_Codes_Step3 $\setminus$ {WPW_Syndrome, NDS3}
grd6 : ST_elevation(V1) = TRUE $\wedge$
ST_elevation(V2) = TRUE
grd7 : Sinus = Yes

then

act1 : Disease_step3 := Brugada_Syndrome

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int $\geq$ 110
grd4 : dis $\in$ Disease_Codes_Step3 $\setminus$ {WPW_Syndrome, Brugada_Syndrome, NDS3}
grd5 : Epsilon_Wave(V1) = TRUE $\wedge$
Epsilon_Wave(V3) = TRUE

then

act1 : Disease_step3 := RV_Dysplasia

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$

ST segment elevation...

refines *ST_seg_elevation_YES*

when

grd1 : $Heart\_State = KO$

grd2 : $Sinus = Yes$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $Disease\_step4 \in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$

then

act1 : $Disease\_step4 := STEMI$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$

Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \in \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$
Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\lor$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \land ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \land \mathtt{k} \in \mathtt{LEADS} \land$
$(\mathtt{ST\_depression}(\mathtt{l}) \geq 1000 \land \mathtt{ST\_depression}(\mathtt{k}) \geq 1000)$
$\land\, \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \notin \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : $\mathtt{Q\_Width}(\mathtt{II}) < 40 \land \mathtt{Q\_Depth}(\mathtt{II}) \leq 3000 \land$
$\mathtt{Q\_Width}(\mathtt{aVF}) < 40 \land \mathtt{Q\_Depth}(\mathtt{aVF}) \leq 3000 \land$
$\mathtt{Q\_Width}(\mathtt{aVL}) < 40$

1000 micrometer= 1 milimeter

grd2 : $\mathtt{Q\_Width}(\mathtt{III}) \leq 40 \land \mathtt{Q\_Depth}(\mathtt{III}) \leq 7000 \land \mathtt{Q\_Depth}(\mathtt{aVL}) \leq 7000$

grd3 : $\mathtt{Q\_Depth}(\mathtt{I}) < 40 \land \mathtt{Q\_Depth}(\mathtt{I}) \leq 1500$

then

act1 : $\mathtt{Q\_Normal\_Status} := \mathtt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\lor$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$
$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$
$\land$
$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$
$\land\, l1 \neq k1$
$\land$
$($
$(l1 = V1 \land k1 = V2) \lor$
$(l1 = V2 \land k1 = V3) \lor$
$(l1 = V3 \land k1 = V4) \lor$

$(l1 = V4 \land k1 = V5) \lor$
$(l1 = V5 \land k1 = V6)$
$)$
$))$
grd4 : $\mathtt{Q\_Width(V5)} \geq 40 \land \mathtt{Q\_Depth(V5)} > 3000 \land$
$\mathtt{Q\_Width(V6)} \geq 40 \land \mathtt{Q\_Depth(V6)} > 3000$
grd5 : $\mathtt{Q\_Width(aVL)} \geq 40 \land \mathtt{Q\_Depth(aVL)} > 7000$
grd6 : $\mathtt{Q\_Depth(I)} \geq 40 \land \mathtt{Q\_Depth(I)} > 1500$
grd7 : $\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Acute\_anterior\_MI}$

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd2 : $\mathtt{Sinus} = \mathtt{Yes}$
grd3 : $\lor$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$
$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$
$\land$
$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$
$\land l1 \neq k1$
$\land$
$($
$(l1 = V1 \land k1 = V2) \lor$
$(l1 = V2 \land k1 = V3) \lor$
$(l1 = V3 \land k1 = V4) \lor$
$(l1 = V4 \land k1 = V5) \lor$
$(l1 = V5 \land k1 = V6)$
$)$
$))$
grd4 : $\mathtt{Q\_Width(II)} \geq 40 \land \mathtt{Q\_Depth(II)} > 3000 \land$
$\mathtt{Q\_Width(III)} > 40 \land \mathtt{Q\_Depth(III)} > 7000 \land$
$\mathtt{Q\_Width(aVF)} \geq 40 \land \mathtt{Q\_Depth(aVF)} > 3000$
grd5 : $\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Acute\_inferior\_MI}$

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\mathtt{Disease\_step4} = \mathtt{Acute\_inferior\_MI}$
$\lor$
$\mathtt{Disease\_step5} \in \{\mathtt{anterior\_MI}, \mathtt{LVH}, \mathtt{emphysema}\}$
$\lor$
$\mathtt{Mice\_State} = \mathtt{Exclude\_Mimics\_MI}$
$\lor$
$\mathtt{Disease\_step2} = \mathtt{LBBB}$

then

act1 : $\texttt{Age\_of\_Inf} :\in \{\texttt{recent}, \texttt{old}, \texttt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd2 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act1 : $\texttt{Disease\_step5} := \texttt{Hypertrophic\_cardiomyopathy}$

act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth}(\texttt{V1}) \geq 0 \land \texttt{R\_Depth}(\texttt{V1}) \leq 6000 \land \texttt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth}(\texttt{V2}) > 200 \land \texttt{R\_Depth}(\texttt{V2}) \leq 12000$

grd3 : $\texttt{R\_Depth}(\texttt{V2}) \geq 1000 \land \texttt{R\_Depth}(\texttt{V2}) \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} :\in \{\texttt{late\_transition}, \texttt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$

act2 : $\texttt{Mice\_State} := \texttt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\texttt{Q\_Wave\_State(V5)} = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State(V6)} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{lateral\_MI}, \texttt{Hypertrophic\_cardiomyopathy}\}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

when

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step6 :\in \{RAE, RVH, RV\_strain, pulmonary\_embolism\}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

when

grd1 : $(P\_Wave\_Peak(II) < 3000 \wedge$
$P\_Wave\_Peak(V1) < 3000)$
$\vee$
$(P\_Wave\_Broad(II) < 110 \wedge P\_Wave\_Broad(V1) < 110) \vee$
$Diphasic(II) = FALSE \vee$
$Diphasic(V1) = FALSE$

then

act1 : $Disease\_step6 := NDS6$

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

when

grd1 : $(P\_Wave\_Broad(II) \geq 110 \wedge P\_Wave\_Broad(V1) \geq 110) \vee$
$Diphasic(II) = TRUE \vee$
$Diphasic(V1) = TRUE$

grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step6 :\in \{LAE, mitral\_stenosis, mitral\_regurgitation, LV\_failure,$
$dilated\_cardiomyopathy, LVH\_cause\}$

end

END

An Event-B Specification of Step6_P_Wave_Ref1
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MACHINE Step6_P_Wave_Ref1

REFINES Step6_P_Wave

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx

VARIABLES

- `RR_Int_equidistant` RR Interval
- `PP_Int_equidistant` PP Interval
- `P_Positive` P wave positive or negative
- `Sinus` Sinus Rhythm
- `Heart_Rate` Heart Rate in BPM
- `Heart_State` OK or KO for heart state after ECG Interpretation
- `PR_Int` PR Interval
- `Disease_step2` At level 2 Disease Codes
- `QRS_Int` QRS Interval
- `M_Shape_Complex` M-shaped complex in Leads
- `Slurred_S` Slurred S wave in Leads
- `Notched_R` Notched R wave in Leads
- `Small_R_QS` A small R or QS wave in V1 and V2
- `Slurred_S_duration` Slurred S duration
- `Delta_Wave` Delta Wave
- `Disease_step3`
- `ST_elevation` ST segment elevation (Coved or Saddle-back)
- `Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
- `PP_Interval`
- `RR_Interval`
- `ST_seg_ele` ST segment for elevation 1mm=0.1mV
- `Disease_step4`
- `Q_Width` Q wave width
- `Q_Depth` Q wave depth
- `Q_Normal_Status` Q wave normal or abnormal
- `Age_of_Inf` Age of Infarct
- `Disease_step5`
- `Mice_State`
- `R_Depth` R wave depth or height
- `R_Normal_Status` R wave normal or abnormal
- `Q_Wave_State` Q wave states for all LEADS
- `P_Wave_Peak` function to estimate the peak of LEADS signal
- `Disease_step6`
- `Diphasic`
- `P_Wave_Broad`
- `ST_depression`

INVARIANTS

inv1 : $Sinus = Yes \wedge Disease\_step6 = LAE \Rightarrow Heart\_State = KO$

inv2 : $Sinus = Yes \wedge Disease\_step6 = RAE \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $\mathtt{RR\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act2 : $\mathtt{PP\_Int\_equidistant} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act3 : $\mathtt{P\_Positive} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act4 : $\mathtt{Sinus} := \mathtt{No}$
act5 : $\mathtt{PP\_Interval} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act6 : $\mathtt{RR\_Interval} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act7 : $\mathtt{Heart\_Rate} :\in 1 \,..\, 300$
act8 : $\mathtt{Heart\_State} := \mathtt{KO}$
act9 : $\mathtt{PR\_Int} := 120$
act10 : $\mathtt{Disease\_step2} := \mathtt{NDS2}$
act11 : $\mathtt{QRS\_Int} := 50$
act12 : $\mathtt{Notched\_R} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act13 : $\mathtt{Small\_R\_QS} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act14 : $\mathtt{Slurred\_S\_duration} :\in \mathtt{LEADS} \rightarrow \mathbb{N}_1$
act15 : $\mathtt{M\_Shape\_Complex} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act16 : $\mathtt{Slurred\_S} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act17 : $\mathtt{ST\_elevation} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act18 : $\mathtt{Epsilon\_Wave} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act19 : $\mathtt{Delta\_Wave} := 0$
act20 : $\mathtt{Disease\_step3} := \mathtt{NDS3}$
act21 : $\mathtt{ST\_seg\_ele} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act22 : $\mathtt{Disease\_step4} := \mathtt{NDS4}$
act57 : $\mathtt{ST\_depression} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act23 : $\mathtt{Q\_Width} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act24 : $\mathtt{Q\_Depth} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act25 : $\mathtt{Q\_Normal\_Status} := \mathtt{FALSE}$
act26 : $\mathtt{Mice\_State} := \mathtt{NMS}$
act27 : $\mathtt{R\_Depth} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act28 : $\mathtt{R\_Normal\_Status} := \mathtt{FALSE}$
act29 : $\mathtt{Q\_Wave\_State} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act30 : $\mathtt{Age\_of\_Inf} :\in \mathtt{Age\_of\_Infarct}$
act31 : $\mathtt{Disease\_step5} := \mathtt{NDS5}$
act32 : $\mathtt{Diphasic} :\in \mathtt{LEADS} \rightarrow \mathtt{BOOL}$
act33 : $\mathtt{P\_Wave\_Broad} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act34 : $\mathtt{P\_Wave\_Peak} :\in \mathtt{LEADS} \rightarrow \mathbb{N}$
act35 : $\mathtt{Disease\_step6} := \mathtt{NDS6}$

end

Event *Rhythm_test_TRUE* $\widehat{=}$

Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd4 : $rate \in 60 .. 100$

60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$

Heart is Normal if PR $\leq$ 200 QRS_Int < 120

$HeartisNormalifQRS < 120$

grd6grd7 : $Disease\_step2 = NDS2$

grd8 : $Disease\_step3 = NDS3$

grd9 : $Disease\_step4 = NDS4$

grd10 : $Disease\_step5 = NDS5$

grd11 : $Disease\_step6 = NDS6$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$

Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $rate \in 1 .. 300$

then

act1 : $Sinus := No$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd5 : $rate \in 1 .. 300 \setminus 60 .. 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $Disease\_step3 = WPW\_Syndrome \lor Disease\_step3 = Brugada\_Syndrome \lor$
$Disease\_step3 = RV\_Dysplasia \lor Disease\_step3 = IVCD$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $pr \in 120 .. 220$

time interval in (ms.)

grd2 : $pr > 200$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

then

act1 : $PR\_Int := pr$

act2 : $Disease\_step2 := First\_degree\_AV\_Block$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $qrs \in 50 .. 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $Notched\_R(I) = TRUE \land$
$Notched\_R(V5) = TRUE \land$
$Notched\_R(V6) = TRUE$

Right Bundle Branch Block (RBBB)

grd6 : $Small\_R\_QS(V1) = TRUE \land$
$Small\_R\_QS(V2) = TRUE$

grd7 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$
from step 5
grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$
from step 5

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$
act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$
grd2 : $\texttt{qrs} \geq 120$
grd3 : $\texttt{Sinus} = \texttt{Yes}$
grd4 : $\texttt{Heart\_State} = \texttt{KO}$
grd5 : $\texttt{M\_Shape\_Complex}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{M\_Shape\_Complex}(\texttt{V2}) = \texttt{TRUE}$
grd7 : $\texttt{Slurred\_S}(\texttt{I}) = \texttt{TRUE} \land$
$\texttt{Slurred\_S}(\texttt{V5}) = \texttt{TRUE} \land$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{TRUE}$
grd8 : $\texttt{Slurred\_S\_duration}(\texttt{I}) > 40 \land$
$\texttt{Slurred\_S\_duration}(\texttt{V5}) > 40 \land$
$\texttt{Slurred\_S\_duration}(\texttt{V6}) > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$
act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave
exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$
grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \lor \texttt{sympt} = \texttt{A\_LBBB}$
grd3 : $\texttt{d\_wave} \in \mathbb{N}$
grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$
Delta Wave + PR $\leq$ 120 Heart_State = KO
grd5grd6 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd7 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act2 : $\texttt{Delta\_Wave} := \texttt{d\_wave}$

act3 : $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{Slurred\_S}(\texttt{V5}) = \texttt{FALSE} \land$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{FALSE}$

grd5 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$

grd6 : $\texttt{ST\_elevation}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{ST\_elevation}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Sinus} = \texttt{Yes}$

then

act1 : $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$

Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$

grd5 : $\texttt{Epsilon\_Wave}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{Epsilon\_Wave}(\texttt{V3}) = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$

IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event $ST\_seg\_elevation\_YES \mathrel{\widehat{=}}$

ST segment elevation...

extends $ST\_seg\_elevation\_YES$

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event $ST\_seg\_elevation\_NOTCKMB\_Yes \mathrel{\widehat{=}}$

Troponin or CK-MB positive YES

extends $ST\_seg\_elevation\_NOTCKMB\_Yes$

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression(l)} \geq 1000 \wedge \texttt{ST\_depression(k)} \geq 1000)$
$\wedge \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \in \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$
Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \notin \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : $\texttt{Q\_Width}(\texttt{II}) < 40 \wedge \texttt{Q\_Depth}(\texttt{II}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVF}) < 40 \wedge \texttt{Q\_Depth}(\texttt{aVF}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVL}) < 40$

1000 micrometer= 1 milimeter

grd2 : $\texttt{Q\_Width}(\texttt{III}) \leq 40 \wedge \texttt{Q\_Depth}(\texttt{III}) \leq 7000 \wedge \texttt{Q\_Depth}(\texttt{aVL}) \leq 7000$

grd3 : $\texttt{Q\_Depth}(\texttt{I}) < 40 \wedge \texttt{Q\_Depth}(\texttt{I}) \leq 1500$

then

act1 : $\texttt{Q\_Normal\_Status} := \texttt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$

$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\texttt{Q\_Width(V5)} \geq 40 \wedge \texttt{Q\_Depth(V5)} > 3000 \wedge$
$\texttt{Q\_Width(V6)} \geq 40 \wedge \texttt{Q\_Depth(V6)} > 3000$

grd5 : $\texttt{Q\_Width(aVL)} \geq 40 \wedge \texttt{Q\_Depth(aVL)} > 7000$

grd6 : $\texttt{Q\_Depth(I)} \geq 40 \wedge \texttt{Q\_Depth(I)} > 1500$

grd7 : $\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Acute\_anterior\_MI}$

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\texttt{Q\_Width(II)} \geq 40 \wedge \texttt{Q\_Depth(II)} > 3000 \wedge$
$\texttt{Q\_Width(III)} > 40 \wedge \texttt{Q\_Depth(III)} > 7000 \wedge$
$\texttt{Q\_Width(aVF)} \geq 40 \wedge \texttt{Q\_Depth(aVF)} > 3000$

grd5 : $\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Acute\_inferior\_MI}$

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$
$\vee$
$\texttt{Disease\_step5} \in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$
$\vee$
$\texttt{Mice\_State} = \texttt{Exclude\_Mimics\_MI}$
$\vee$
$\texttt{Disease\_step2} = \texttt{LBBB}$

then

act1 : $\texttt{Age\_of\_Inf} :\in \{\texttt{recent}, \texttt{old}, \texttt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd2 : $\texttt{exmi} \in \texttt{Mice\_State5} \wedge \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act1 : $\texttt{Disease\_step5} := \texttt{Hypertrophic\_cardiomyopathy}$

act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth}(\texttt{V1}) \geq 0 \wedge \texttt{R\_Depth}(\texttt{V1}) \leq 6000 \wedge \texttt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth}(\texttt{V2}) > 200 \wedge \texttt{R\_Depth}(\texttt{V2}) \leq 12000$

grd3 : $\texttt{R\_Depth}(\texttt{V2}) \geq 1000 \wedge \texttt{R\_Depth}(\texttt{V2}) \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} :\in \{\texttt{late\_transition}, \texttt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$

grd3 : $\mathtt{Heart\_State = KO}$

then

act1 : $\mathtt{Disease\_step5 :\in \{anterior\_MI, LVH, emphysema\}}$

act2 : $\mathtt{Mice\_State := Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\mathtt{Q\_Wave\_State(V5) = TRUE} \land$
$\mathtt{Q\_Wave\_State(V6) = TRUE}$

grd3 : $\mathtt{Heart\_State = KO}$

then

act1 : $\mathtt{Disease\_step5 :\in \{lateral\_MI, Hypertrophic\_cardiomyopathy\}}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $\mathtt{(P\_Wave\_Peak(II) < 3000} \land$
$\mathtt{P\_Wave\_Peak(V1) < 3000)}$
$\lor$
$\mathtt{(P\_Wave\_Broad(II) < 110 \land P\_Wave\_Broad(V1) < 110)} \lor$
$\mathtt{Diphasic(II) = FALSE} \lor$
$\mathtt{Diphasic(V1) = FALSE}$

then

act1 : $\mathtt{Disease\_step6 := NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

refines *P_Wave_assessment_Peaked_Yes*

when

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step6 := RAE$

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

refines *P_Wave_assessment_Peaked_Yes*

when

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Heart\_State = KO$

grd4 : $Disease\_step6 = RAE$

then

act1 : $Disease\_step6 :\in \{RVH, RV\_strain, pulmonary\_embolism\}$

end

Event $P\_Wave\_assessment\_Broad\_Yes \;\widehat{=}$

refines $P\_Wave\_assessment\_Broad\_Yes$

when

grd1 : $(P\_Wave\_Broad(II) \geq 110 \land P\_Wave\_Broad(V1) \geq 110) \lor$
$Diphasic(II) = TRUE \lor$
$Diphasic(V1) = TRUE$

grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step6 := LAE$

end

Event $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE \;\widehat{=}$

refines $P\_Wave\_assessment\_Broad\_Yes$

when

grd1 : $(P\_Wave\_Broad(II) \geq 110 \land P\_Wave\_Broad(V1) \geq 110) \lor$
$Diphasic(II) = TRUE \lor$
$Diphasic(V1) = TRUE$

grd2 : $Heart\_State = KO$

grd3 : $Disease\_step6 = LAE$

then

act1 : $Disease\_step6 :\in \{mitral\_stenosis, mitral\_regurgitation, LV\_failure,$
$dilated\_cardiomyopathy, LVH\_cause\}$

end

END

An Event-B Specification of Step7_LVH_RVH
Generated Date: 25 Nov 2010 @ 03:39:32 PM

MACHINE Step7_LVH_RVH

REFINES Step6_P_Wave_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

`ST_seg_ele` ST segment for elevation 1mm=0.1mV

`Disease_step4`

`Q_Width` Q wave width

`PP_Interval`

`RR_Interval`

`Q_Depth` Q wave depth

`Q_Normal_Status` Q wave normal or abnormal

`Age_of_Inf` Age of Infarct

`Disease_step5`

`Mice_State`

`R_Depth` R wave depth or height (also use in Step 7)

`R_Normal_Status` R wave normal or abnormal

`Q_Wave_State` Q wave states for all LEADS

`P_Wave_Peak` function to estimate the peak of LEADS signal

`Disease_step6`

`Diphasic`

`P_Wave_Broad`

`S_Depth` S wave depth or height

R_S_Ratio R wave and S wave Ratio function

ST_depression

INVARIANTS

inv1 : $S\_Depth \in LEADS \to \mathbb{N}$

inv2 : $R\_S\_Ratio \in LEADS \to \mathbb{N}$

inv3 : $Sinus = Yes \land Disease\_step6 = RVH \Rightarrow Heart\_State = KO$

inv4 : $Sinus = Yes \land Disease\_step6 = LVH\_cause \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : RR_Int_equidistant $:\in$ LEADS $\to$ BOOL

act2 : PP_Int_equidistant $:\in$ LEADS $\to$ BOOL

act3 : P_Positive $:\in$ LEADS $\to$ BOOL

act4 : Sinus $:=$ No

act5 : PP_Interval $:\in$ LEADS $\to \mathbb{N}$

act6 : RR_Interval $:\in$ LEADS $\to \mathbb{N}$

act7 : Heart_Rate $:\in$ 1 .. 300

act8 : Heart_State $:=$ KO

act9 : PR_Int $:=$ 120

act10 : Disease_step2 $:=$ NDS2

act11 : QRS_Int $:=$ 50

act12 : Notched_R $:\in$ LEADS $\to$ BOOL

act13 : Small_R_QS $:\in$ LEADS $\to$ BOOL

act14 : Slurred_S_duration $:\in$ LEADS $\to \mathbb{N}_1$

act15 : M_Shape_Complex $:\in$ LEADS $\to$ BOOL

act16 : Slurred_S $:\in$ LEADS $\to$ BOOL

act17 : ST_elevation $:\in$ LEADS $\to$ BOOL

act18 : Epsilon_Wave $:\in$ LEADS $\to$ BOOL

act19 : Delta_Wave $:=$ 0

act20 : Disease_step3 $:=$ NDS3

act21 : ST_seg_ele $:\in$ LEADS $\to \mathbb{N}$

act22 : Disease_step4 $:=$ NDS4

act57 : ST_depression $:\in$ LEADS $\to \mathbb{N}$

act23 : Q_Width $:\in$ LEADS $\to \mathbb{N}$

act24 : Q_Depth $:\in$ LEADS $\to \mathbb{N}$

act25 : Q_Normal_Status $:=$ FALSE

act26 : Mice_State $:=$ NMS

act27 : R_Depth $:\in$ LEADS $\to \mathbb{N}$

act28 : R_Normal_Status $:=$ FALSE

act29 : Q_Wave_State $:\in$ LEADS $\to$ BOOL

act30 : Age_of_Inf $:\in$ Age_of_Infarct

act31 : Disease_step5 $:=$ NDS5

act32 : Diphasic $:\in$ LEADS $\to$ BOOL

act33 : P_Wave_Broad $:\in$ LEADS $\to \mathbb{N}$

act34 : P_Wave_Peak $:\in$ LEADS $\to \mathbb{N}$

act35 : Disease_step6 $:=$ NDS6

act36 : $S\_Depth :\in LEADS \rightarrow \mathbb{N}$
act37 : $R\_S\_Ratio :\in LEADS \rightarrow \mathbb{N}$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land RR\_Int\_equidistant(l) = TRUE \land RR\_Interval(l) = PP\_Interval(l)) \land P\_Positive(II) = TRUE$

grd4 : $rate \in 60 \,..\, 100$
60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$
Heart is Normal if PR ≤ 200 QRS_Int < 120
$HeartisNormalifQRS < 120$

grd6grd7 : $Disease\_step2 = NDS2$

grd8 : $Disease\_step3 = NDS3$

grd9 : $Disease\_step4 = NDS4$

grd10 : $Disease\_step5 = NDS5$

grd11 : $Disease\_step6 = NDS6$

then

act1 : $Sinus := Yes$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor RR\_Int\_equidistant(l) = FALSE \lor RR\_Interval(l) \neq PP\_Interval(l)) \lor P\_Positive(II) = FALSE$

grd2 : $rate \in 1 \,..\, 300$

then

act1 : $Sinus := No$
act2 : $Heart\_Rate := rate$
act3 : $Heart\_State := KO$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd5 : $rate \in 1 \mathbin{..} 300 \setminus 60 \mathbin{..} 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $Disease\_step3 = WPW\_Syndrome \lor Disease\_step3 = Brugada\_Syndrome \lor$
$Disease\_step3 = RV\_Dysplasia \lor Disease\_step3 = IVCD$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $pr \in 120 \mathbin{..} 220$
time interval in (ms.)

grd2 : $pr > 200$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

then

act1 : $PR\_Int := pr$

act2 : $Disease\_step2 := First\_degree\_AV\_Block$

end

Event *QRS_Test_LBBB* $\widehat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $qrs \in 50 \mathbin{..} 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $\texttt{Notched\_R}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V6}) = \texttt{TRUE}$
Right Bundle Branch Block (RBBB)
grd6 : $\texttt{Small\_R\_QS}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Small\_R\_QS}(\texttt{V2}) = \texttt{TRUE}$
grd7 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$
from step 5
grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$
from step 5

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$
act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$
grd2 : $\texttt{qrs} \geq 120$
grd3 : $\texttt{Sinus} = \texttt{Yes}$
grd4 : $\texttt{Heart\_State} = \texttt{KO}$
grd5 : $\texttt{M\_Shape\_Complex}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{M\_Shape\_Complex}(\texttt{V2}) = \texttt{TRUE}$
grd7 : $\texttt{Slurred\_S}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{TRUE}$
grd8 : $\texttt{Slurred\_S\_duration}(\texttt{I}) > 40 \wedge$
$\texttt{Slurred\_S\_duration}(\texttt{V5}) > 40 \wedge$
$\texttt{Slurred\_S\_duration}(\texttt{V6}) > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$
act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave
exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$

$\texttt{grd2} :$ $\texttt{sympt} = \texttt{A\_RBBB} \lor \texttt{sympt} = \texttt{A\_LBBB}$

$\texttt{grd3} :$ $\texttt{d\_wave} \in \mathbb{N}$

$\texttt{grd4} :$ $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$

Delta Wave + PR $\leq$ 120 `Heart_State = KO`

grd5grd6 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

$\texttt{grd7} :$ $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

$\texttt{act2} :$ $\texttt{Delta\_Wave} := \texttt{d\_wave}$

$\texttt{act3} :$ $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt

dis

where

$\texttt{grd1} :$ $\texttt{sympt} = \texttt{A\_RBBB}$

$\texttt{grd2} :$ $\texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd3} :$ $\texttt{QRS\_Int} \geq 110$

$\texttt{grd4} :$ $\texttt{Slurred\_S}(\texttt{V5}) = \texttt{FALSE} \land$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{FALSE}$

$\texttt{grd5} :$ $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$

$\texttt{grd6} :$ $\texttt{ST\_elevation}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{ST\_elevation}(\texttt{V2}) = \texttt{TRUE}$

$\texttt{grd7} :$ $\texttt{Sinus} = \texttt{Yes}$

then

$\texttt{act1} :$ $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$

Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt

dis

where

$\texttt{grd1} :$ $\texttt{sympt} = \texttt{A\_RBBB}$

$\texttt{grd2} :$ $\texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd3} :$ $\texttt{QRS\_Int} \geq 110$

$\texttt{grd4} :$ $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$

$\texttt{grd5} :$ $\texttt{Epsilon\_Wave}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{Epsilon\_Wave}(\texttt{V3}) = \texttt{TRUE}$

then

$\texttt{act1} :$ $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event $QRS\_Test\_Atypical\_RBBB\_IVCD \widehat{=}$
IVCD diagnosis

extends $QRS\_Test\_Atypical\_RBBB\_IVCD$

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event $ST\_seg\_elevation\_YES \widehat{=}$
ST segment elevation...

extends $ST\_seg\_elevation\_YES$

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\lor$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$
$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$
$\land$
$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$
$\land l1 \neq k1$
$\land$
$($
$(l1 = V1 \land k1 = V2) \lor$
$(l1 = V2 \land k1 = V3) \lor$
$(l1 = V3 \land k1 = V4) \lor$
$(l1 = V4 \land k1 = V5) \lor$
$(l1 = V5 \land k1 = V6)$
$)$
$))$

grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event $ST\_seg\_elevation\_NOTCKMB\_Yes \widehat{=}$
Troponin or CK-MB positive YES

extends $ST\_seg\_elevation\_NOTCKMB\_Yes$

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\lor$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \land ST\_seg\_ele(l1) < 1000))$

$\text{grd4}: \exists l, k \cdot l \in LEADS \land k \in LEADS \land$
$(ST\_depression(l) \geq 1000 \land ST\_depression(k) \geq 1000)$
$\land l \neq k$

$\text{grd5}: Disease\_step4 \in \{Troponin, CK\_MB\}$

then

$\text{act1}: Disease\_step4 := Non\_STEMI$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$
Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

$\text{grd1}: Heart\_State = KO$

$\text{grd2}: Sinus = Yes$

$\text{grd3}: \quad \lor$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \land ST\_seg\_ele(l1) < 1000))$

$\text{grd4}: \exists l, k \cdot l \in LEADS \land k \in LEADS \land$
$(ST\_depression(l) \geq 1000 \land ST\_depression(k) \geq 1000)$
$\land l \neq k$

$\text{grd5}: Disease\_step4 \notin \{Troponin, CK\_MB\}$

then

$\text{act1}: Disease\_step4 := Ischemia$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

$\text{grd1}: Q\_Width(II) < 40 \land Q\_Depth(II) \leq 3000 \land$
$Q\_Width(aVF) < 40 \land Q\_Depth(aVF) \leq 3000 \land$
$Q\_Width(aVL) < 40$

1000 micrometer= 1 milimeter

$\text{grd2}: Q\_Width(III) \leq 40 \land Q\_Depth(III) \leq 7000 \land Q\_Depth(aVL) \leq 7000$

$\text{grd3}: Q\_Depth(I) < 40 \land Q\_Depth(I) \leq 1500$

then

$\text{act1}: Q\_Normal\_Status := TRUE$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

$\text{grd1}: Heart\_State = KO$

$\text{grd2}: Sinus = Yes$

grd3 : $\vee$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$
grd4 : $\texttt{Q\_Width(V5)} \geq 40 \wedge \texttt{Q\_Depth(V5)} > 3000 \wedge$
$\texttt{Q\_Width(V6)} \geq 40 \wedge \texttt{Q\_Depth(V6)} > 3000$
grd5 : $\texttt{Q\_Width(aVL)} \geq 40 \wedge \texttt{Q\_Depth(aVL)} > 7000$
grd6 : $\texttt{Q\_Depth(I)} \geq 40 \wedge \texttt{Q\_Depth(I)} > 1500$
grd7 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_anterior_MI

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$
Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO
grd2 : Sinus = Yes
grd3 : $\vee$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$
grd4 : $\texttt{Q\_Width(II)} \geq 40 \wedge \texttt{Q\_Depth(II)} > 3000 \wedge$
$\texttt{Q\_Width(III)} > 40 \wedge \texttt{Q\_Depth(III)} > 7000 \wedge$
$\texttt{Q\_Width(aVF)} \geq 40 \wedge \texttt{Q\_Depth(aVF)} > 3000$
grd5 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_inferior_MI

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$
$\lor$
$\texttt{Disease\_step5} \in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$
$\lor$
$\texttt{Mice\_State} = \texttt{Exclude\_Mimics\_MI}$
$\lor$
$\texttt{Disease\_step2} = \texttt{LBBB}$

then

act1 : $\texttt{Age\_of\_Inf} :\in \{\texttt{recent}, \texttt{old}, \texttt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd2 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act1 : $\texttt{Disease\_step5} := \texttt{Hypertrophic\_cardiomyopathy}$

act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth}(\texttt{V1}) \geq 0 \land \texttt{R\_Depth}(\texttt{V1}) \leq 6000 \land \texttt{age} > 30$
1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth}(\texttt{V2}) > 200 \land \texttt{R\_Depth}(\texttt{V2}) \leq 12000$

grd3 : $\texttt{R\_Depth}(\texttt{V2}) \geq 1000 \land \texttt{R\_Depth}(\texttt{V2}) \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} :\in \{\texttt{late\_transition}, \texttt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$
R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$
grd2 : $\mathtt{Q\_Wave\_State(V1)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V2)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V3)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V4)} = \mathtt{TRUE}$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} :\in \{\mathtt{anterior\_MI}, \mathtt{LVH}, \mathtt{emphysema}\}$
act2 : $\mathtt{Mice\_State} := \mathtt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$
R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\mathtt{Q\_Wave\_State(V5)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V6)} = \mathtt{TRUE}$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} :\in \{\mathtt{lateral\_MI}, \mathtt{Hypertrophic\_cardiomyopathy}\}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $(\mathtt{P\_Wave\_Peak(II)} < 3000 \land$
$\mathtt{P\_Wave\_Peak(V1)} < 3000)$
$\lor$
$(\mathtt{P\_Wave\_Broad(II)} < 110 \land \mathtt{P\_Wave\_Broad(V1)} < 110) \lor$
$\mathtt{Diphasic(II)} = \mathtt{FALSE} \lor$
$\mathtt{Diphasic(V1)} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : $\mathtt{P\_Wave\_Peak(II)} \geq 3000$
grd2 : $\mathtt{P\_Wave\_Peak(V1)} \geq 3000$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RAE}$

end

Event $P\_Wave\_assessment\_Peaked\_Yes\_Check\_RAE \triangleq$

refines $P\_Wave\_assessment\_Peaked\_Yes\_Check\_RAE$

when

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Disease\_step6 = RAE$

grd4 : $Heart\_State = KO$

then

act1 : $Disease\_step6 :\in \{RV\_strain, pulmonary\_embolism\}$

end

Event $P\_Wave\_assessment\_Broad\_Yes \triangleq$

extends $P\_Wave\_assessment\_Broad\_Yes$

when

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \wedge \texttt{P\_Wave\_Broad(V1)} \geq 110) \vee$
$\texttt{Diphasic(II)} = \texttt{TRUE} \vee$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{LAE}$

end

Event $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE \triangleq$

refines $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE$

when

grd1 : $(P\_Wave\_Broad(II) \geq 110 \wedge P\_Wave\_Broad(V1) \geq 110) \vee$
$Diphasic(II) = TRUE \vee$
$Diphasic(V1) = TRUE$

grd2 : $Disease\_step6 = LAE$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step6 :\in \{mitral\_stenosis, mitral\_regurgitation, LV\_failure, dilated\_cardiomyopathy\}$

end

Event $LVH\_Assessment \triangleq$

LVH Assessment

refines $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE$

any

$LVH\_specificity$ specificity in percentage

$sensitivity$ sensitivity in percentage

sex

where

grd1 : $(P\_Wave\_Broad(II) \geq 110 \wedge P\_Wave\_Broad(V1) \geq 110) \vee$
$Diphasic(II) = TRUE \vee$
$Diphasic(V1) = TRUE$

grd2 : $Disease\_step6 = LAE$
grd5 : $sex \in \{0, 1\}$
o for men and 1 for women
grd3 : $((S\_Depth(V1) + R\_Depth(V5)) > 35000$
$\lor$
$(S\_Depth(V1) + R\_Depth(V6)) > 35000)$
1mm = 1000 micrometer............. 1 assessment
grd4 : $((R\_Depth(aVL) + S\_Depth(V1) \geq 24000) \land sex = 0)$
$\lor$
$((R\_Depth(aVL) + S\_Depth(V1) \geq 18000) \land sex = 1)$
2 assessment
grd6 : $LVH\_specificity = 90$
$\land$
$sensitivity < 40$
1 and 2 assessment
grd7 : $Disease\_step6 = LAE \Rightarrow LVH\_specificity < 98$
3 assesssment
grd8 : $Heart\_State = KO$
then
act1 : $Disease\_step6 := LVH\_cause$
end

Event $RVH\_Assessment \;\widehat{=}$
RVH Assessment

refines $P\_Wave\_assessment\_Peaked\_Yes\_Check\_RAE$

any
age age od men or women
$aixs$ axis for deviation
where
grd1 : $P\_Wave\_Peak(II) \geq 3000$
grd2 : $P\_Wave\_Peak(V1) \geq 3000$
grd3 : $Disease\_step6 = RAE$
grd4 : $R\_Depth(V1) \geq 7000 \land age > 30$
1 assessment
grd5 : $S\_Depth(V5) \geq 7000 \lor$
$S\_Depth(V6) \geq 7000$
2 assessment
grd6 : $R\_S\_Ratio(V1) \geq 100$
R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
grd7 : $R\_S\_Ratio(V5) \leq 100$
$\lor$
$R\_S\_Ratio(V6) \leq 100$
4 assessment
grd8 : $aixs \in 0 \,..\, 360 \land aixs \geq 110$
5 assessment
grd9 : $Disease\_step2 \notin \{LBBB, RBBB\}$
grd10 : $QRS\_Int < 120$
grd11 : $Heart\_State = KO$
then
act1 : $Disease\_step6 := RVH$
end

END

An Event-B Specification of Step8_ctx
Generated Date: 25 Nov 2010 @ 03:38:48 PM

CONTEXT Step8_ctx

SETS

T_State

Disease_Codes_Step8

T_State_B

T_State_l_d

Disease_states_Codes_step8B

CONSTANTS

Peaked

Flat

Inverted

Hyperkalemia

posterior_MI

Nonspecific_ST_T_changes

Nonspecific

Definite_ischemia

Probable_ischemia

Digitalis_effect

NDS8

Upright

Inverted_B

Variable

Localized

Diffuse

Cardiomyopathy

other_nonspecific

Electrolyte_depletion

Alcohol

Myocarditis

Other

NDS8B

AXIOMS

axm1 : $T\_State = \{Peaked, Flat, Inverted\}$

axm2 : $\neg Peaked = Flat$

axm3 : $\neg Peaked = Inverted$

axm4 : $\neg Flat = Inverted$

axm5 : $Disease\_Codes\_Step8 = \{Hyperkalemia, posterior\_MI, Nonspecific\_ST\_T\_changes, Nonspecific, Definite\_ischemia, Probable\_ischemia, Digitalis\_effect, NDS8\}$

axm6 : $\neg Hyperkalemia = posterior\_MI$

axm7 : $\neg Hyperkalemia = Nonspecific\_ST\_T\_changes$

$\texttt{axm8}: \neg Hyperkalemia = Nonspecific$

$\texttt{axm9}: \neg Hyperkalemia = Definite\_ischemia$

$\texttt{axm10}: \neg Hyperkalemia = Probable\_ischemia$

$\texttt{axm11}: \neg Hyperkalemia = Digitalis\_effect$

$\texttt{axm12}: \neg Hyperkalemia = NDS8$

$\texttt{axm13}: \neg posterior\_MI = Nonspecific\_ST\_T\_changes$

$\texttt{axm14}: \neg posterior\_MI = Nonspecific$

$\texttt{axm15}: \neg posterior\_MI = Definite\_ischemia$

$\texttt{axm16}: \neg posterior\_MI = Probable\_ischemia$

$\texttt{axm17}: \neg posterior\_MI = Digitalis\_effect$

$\texttt{axm18}: \neg posterior\_MI = NDS8$

$\texttt{axm19}: \neg Nonspecific\_ST\_T\_changes = Nonspecific$

$\texttt{axm20}: \neg Nonspecific\_ST\_T\_changes = Definite\_ischemia$

$\texttt{axm21}: \neg Nonspecific\_ST\_T\_changes = Probable\_ischemia$

$\texttt{axm22}: \neg Nonspecific\_ST\_T\_changes = Digitalis\_effect$

$\texttt{axm23}: \neg Nonspecific\_ST\_T\_changes = NDS8$

$\texttt{axm24}: \neg Nonspecific = Definite\_ischemia$

$\texttt{axm25}: \neg Nonspecific = Probable\_ischemia$

$\texttt{axm26}: \neg Nonspecific = Digitalis\_effect$

$\texttt{axm27}: \neg Nonspecific = NDS8$

$\texttt{axm28}: \neg Definite\_ischemia = Probable\_ischemia$

$\texttt{axm29}: \neg Definite\_ischemia = Digitalis\_effect$

$\texttt{axm30}: \neg Definite\_ischemia = NDS8$

$\texttt{axm31}: \neg Probable\_ischemia = Digitalis\_effect$

$\texttt{axm32}: \neg Probable\_ischemia = NDS8$

$\texttt{axm33}: \neg Digitalis\_effect = NDS8$

$\texttt{axm34}: T\_State\_B = \{Upright, Inverted\_B, Variable\}$

$\texttt{axm35}: \neg Upright = Inverted\_B$

$\texttt{axm36}: \neg Upright = Variable$

$\texttt{axm37}: \neg Inverted\_B = Variable$

$\texttt{axm38}: T\_State\_l\_d = \{Localized, Diffuse\}$

$\texttt{axm39}: \neg Localized = Diffuse$

$\texttt{axm40}: Disease\_states\_Codes\_step8B = \{Cardiomyopathy, other\_nonspecific, Electrolyte\_depletion, Alcohol, Myocarditis, Other, NDS8B\}$

$\texttt{axm41}: \neg Cardiomyopathy = other\_nonspecific$

$\texttt{axm42}: \neg Cardiomyopathy = Electrolyte\_depletion$

$\texttt{axm43}: \neg Cardiomyopathy = Alcohol$

$\texttt{axm44}: \neg Cardiomyopathy = Myocarditis$

$\texttt{axm45}: \neg Cardiomyopathy = Other$

$\texttt{axm46}: \neg Cardiomyopathy = NDS8B$

$\texttt{axm47}: \neg other\_nonspecific = Electrolyte\_depletion$

$\texttt{axm48}: \neg other\_nonspecific = Alcohol$

$\texttt{axm49}: \neg other\_nonspecific = Myocarditis$

$\texttt{axm50}: \neg other\_nonspecific = Other$

axm51 : $\neg other\_nonspecific = NDS8B$

axm52 : $\neg Electrolyte\_depletion = Alcohol$

axm53 : $\neg Electrolyte\_depletion = Myocarditis$

axm54 : $\neg Electrolyte\_depletion = Other$

axm55 : $\neg Electrolyte\_depletion = NDS8B$

axm56 : $\neg Alcohol = Myocarditis$

axm57 : $\neg Alcohol = Other$

axm58 : $\neg Alcohol = NDS8B$

axm59 : $\neg Myocarditis = Other$

axm60 : $\neg Myocarditis = NDS8B$

axm61 : $\neg Other = NDS8B$

END

An Event-B Specification of Step8
Generated Date: 25 Nov 2010 @ 03:39:35 PM

MACHINE Step8

REFINES Step7_LVH_RVH

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx

VARIABLES

`RR_Int_equidistant` RR Interval
`PP_Int_equidistant` PP Interval
`P_Positive` P wave positive or negative
`Sinus` Sinus Rhythm
`Heart_Rate` Heart Rate in BPM
`Heart_State` OK or KO for heart state after ECG Interpretation
`PR_Int` PR Interval
`Disease_step2` At level 2 Disease Codes
`QRS_Int` QRS Interval
`M_Shape_Complex` M-shaped complex in Leads
`Slurred_S` Slurred S wave in Leads
`Notched_R` Notched R wave in Leads
`Small_R_QS` A small R or QS wave in V1 and V2
`Slurred_S_duration` Slurred S duration
`Delta_Wave` Delta Wave
`Disease_step3`
`ST_elevation` ST segment elevation (Coved or Saddle-back)
`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
`ST_seg_ele` ST segment for elevation 1mm=0.1mV
`Disease_step4`
`Q_Width` Q wave width
`Q_Depth` Q wave depth
`Q_Normal_Status` Q wave normal or abnormal
`Age_of_Inf` Age of Infarct
`Disease_step5`
`Mice_State`
`PP_Interval`
`RR_Interval`
`R_Depth` R wave depth or height (also use in Step 7)
`R_Normal_Status` R wave normal or abnormal
`Q_Wave_State` Q wave states for all LEADS
`P_Wave_Peak` function to estimate the peak of LEADS signal
`Disease_step6`
`Diphasic`
`P_Wave_Broad`
`S_Depth` S wave depth or height

`R_S_Ratio` R wave and S wave Ratio function

`T_Wave_State` T wave patterns...

`Disease_step8`

`ST_depression`

INVARIANTS

inv1 : $T\_Wave\_State \in LEADS \rightarrow T\_State$

inv2 : $Disease\_step8 \in Disease\_Codes\_Step8$

inv3 : $Sinus = Yes \land Disease\_step8 = Nonspecific \Rightarrow Heart\_State = KO$

inv4 : $Sinus = Yes \land Disease\_step8 = Nonspecific\_ST\_T\_changes \Rightarrow Heart\_State = KO$

inv5 : $Sinus = Yes \land Disease\_step8 = posterior\_MI \Rightarrow Heart\_State = KO$

inv6 : $Sinus = Yes \land Disease\_step8 \in \{Definite\_ischemia, Probable\_ischemia, Digitalis\_effect\}$
$\Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : `RR_Int_equidistant` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act2 : `PP_Int_equidistant` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act3 : `P_Positive` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act4 : `Sinus` $:=$ `No`

act5 : `PP_Interval` $:\in$ `LEADS` $\rightarrow \mathbb{N}$

act6 : `RR_Interval` $:\in$ `LEADS` $\rightarrow \mathbb{N}$

act7 : `Heart_Rate` $:\in 1 \,..\, 300$

act8 : `Heart_State` $:=$ `KO`

act9 : `PR_Int` $:= 120$

act10 : `Disease_step2` $:=$ `NDS2`

act11 : `QRS_Int` $:= 50$

act12 : `Notched_R` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act13 : `Small_R_QS` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act14 : `Slurred_S_duration` $:\in$ `LEADS` $\rightarrow \mathbb{N}_1$

act15 : `M_Shape_Complex` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act16 : `Slurred_S` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act17 : `ST_elevation` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act18 : `Epsilon_Wave` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act19 : `Delta_Wave` $:= 0$

act20 : `Disease_step3` $:=$ `NDS3`

act21 : `ST_seg_ele` $:\in$ `LEADS` $\rightarrow \mathbb{N}$

act22 : `Disease_step4` $:=$ `NDS4`

act57 : `ST_depression` $:\in$ `LEADS` $\rightarrow \mathbb{N}$

act23 : `Q_Width` $:\in$ `LEADS` $\rightarrow \mathbb{N}$

act24 : `Q_Depth` $:\in$ `LEADS` $\rightarrow \mathbb{N}$

act25 : `Q_Normal_Status` $:=$ `FALSE`

act26 : `Mice_State` $:=$ `NMS`

act27 : `R_Depth` $:\in$ `LEADS` $\rightarrow \mathbb{N}$

act28 : `R_Normal_Status` $:=$ `FALSE`

act29 : `Q_Wave_State` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act30 : `Age_of_Inf` $:\in$ `Age_of_Infarct`

act31 : $\mathtt{Disease\_step5} := \mathtt{NDS5}$
act32 : $\mathtt{Diphasic} :\in \mathtt{LEADS} \to \mathtt{BOOL}$
act33 : $\mathtt{P\_Wave\_Broad} :\in \mathtt{LEADS} \to \mathbb{N}$
act34 : $\mathtt{P\_Wave\_Peak} :\in \mathtt{LEADS} \to \mathbb{N}$
act35 : $\mathtt{Disease\_step6} := \mathtt{NDS6}$
act36 : $\mathtt{S\_Depth} :\in \mathtt{LEADS} \to \mathbb{N}$
act37 : $\mathtt{R\_S\_Ratio} :\in \mathtt{LEADS} \to \mathbb{N}$
act38 : $T\_Wave\_State :\in LEADS \to T\_State$
act39 : $Disease\_step8 := NDS8$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any
rate

where
grd1 : $(\exists \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \land \mathtt{PP\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \land$
$\mathtt{RR\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \land$
$\mathtt{RR\_Interval}(\mathtt{l}) = \mathtt{PP\_Interval}(\mathtt{l}))$
$\land$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{TRUE}$
grd4 : $\mathtt{rate} \in 60 \,..\, 100$
60..100 is the range of normal heart rate
grd5 : $\mathtt{PR\_Int} \leq 200$
Heart is Normal if PR ≤ 200 QRS_Int < 120
$Heart is Normal if QRS < 120$
grd6grd7 : $\mathtt{Disease\_step2} = \mathtt{NDS2}$
grd8 : $\mathtt{Disease\_step3} = \mathtt{NDS3}$
grd9 : $\mathtt{Disease\_step4} = \mathtt{NDS4}$
grd10 : $\mathtt{Disease\_step5} = \mathtt{NDS5}$
grd11 : $\mathtt{Disease\_step6} = \mathtt{NDS6}$
grd12 : $Disease\_step8 = NDS8$

then
act1 : $\mathtt{Sinus} := \mathtt{Yes}$
act2 : $\mathtt{Heart\_Rate} := \mathtt{rate}$
act3 : $\mathtt{Heart\_State} := \mathtt{OK}$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any
rate

where
grd1 : $(\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \Rightarrow \mathtt{PP\_Int\_equidistant}(\mathtt{l}) = \mathtt{FALSE} \lor$
$\mathtt{RR\_Int\_equidistant}(\mathtt{l}) = \mathtt{FALSE} \lor$
$\mathtt{RR\_Interval}(\mathtt{l}) \neq \mathtt{PP\_Interval}(\mathtt{l}))$
$\lor$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{FALSE}$

grd2 : $\mathtt{rate} \in 1 \,..\, 300$

then

act1 : $\mathtt{Sinus} := \mathtt{No}$

act2 : $\mathtt{Heart\_Rate} := \mathtt{rate}$

act3 : $\mathtt{Heart\_State} := \mathtt{KO}$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{II}, \mathtt{V1}, \mathtt{V2}\} \wedge \mathtt{PP\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \wedge$
$\mathtt{RR\_Int\_equidistant}(\mathtt{l}) = \mathtt{TRUE} \wedge$
$\mathtt{RR\_Interval}(\mathtt{l}) = \mathtt{PP\_Interval}(\mathtt{l}))$
$\wedge$
$\mathtt{P\_Positive}(\mathtt{II}) = \mathtt{TRUE}$

grd5 : $\mathtt{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $\mathtt{Disease\_step3} = \mathtt{WPW\_Syndrome} \vee \mathtt{Disease\_step3} = \mathtt{Brugada\_Syndrome} \vee$
$\mathtt{Disease\_step3} = \mathtt{RV\_Dysplasia} \vee \mathtt{Disease\_step3} = \mathtt{IVCD}$

then

act1 : $\mathtt{Sinus} := \mathtt{Yes}$

act2 : $\mathtt{Heart\_Rate} := \mathtt{rate}$

act3 : $\mathtt{Heart\_State} := \mathtt{KO}$

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\mathtt{pr} \in 120 \,..\, 220$

time interval in (ms.)

grd2 : $\mathtt{pr} > 200$

grd3 : $\mathtt{Sinus} = \mathtt{Yes}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{PR\_Int} := \mathtt{pr}$

act2 : $\mathtt{Disease\_step2} := \mathtt{First\_degree\_AV\_Block}$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{Notched\_R}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V6}) = \texttt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\texttt{Small\_R\_QS}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Small\_R\_QS}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$

from step 5

grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

from step 5

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$

Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{M\_Shape\_Complex}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{TRUE}$

grd8 : $\texttt{Slurred\_S\_duration}(\texttt{I}) > 40 \wedge$
$\texttt{Slurred\_S\_duration}(\texttt{V5}) > 40 \wedge$
$\texttt{Slurred\_S\_duration}(\texttt{V6}) > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$

QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt

d_wave

exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \lor \texttt{sympt} = \texttt{A\_LBBB}$

grd3 : $\texttt{d\_wave} \in \mathbb{N}$

grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$

Delta Wave + PR $\leq$ 120 Heart_State = KO

grd5grd6 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd7 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act2 : $\texttt{Delta\_Wave} := \texttt{d\_wave}$

act3 : $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{Slurred\_S}(\texttt{V5}) = \texttt{FALSE} \land$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{FALSE}$

grd5 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$

grd6 : $\texttt{ST\_elevation}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{ST\_elevation}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Sinus} = \texttt{Yes}$

then

act1 : $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$

Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$

grd5 : $\texttt{Epsilon\_Wave(V1)} = \texttt{TRUE} \wedge$
$\texttt{Epsilon\_Wave(V3)} = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$
Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$

$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$

$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$

$\wedge\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \in \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$

Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$

$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$

$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$

$\wedge\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \notin \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : $\texttt{Q\_Width}(\texttt{II}) < 40 \wedge \texttt{Q\_Depth}(\texttt{II}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVF}) < 40 \wedge \texttt{Q\_Depth}(\texttt{aVF}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVL}) < 40$

1000 micrometer= 1 milimeter

grd2 : $\texttt{Q\_Width}(\texttt{III}) \leq 40 \wedge \texttt{Q\_Depth}(\texttt{III}) \leq 7000 \wedge \texttt{Q\_Depth}(\texttt{aVL}) \leq 7000$

grd3 : $\texttt{Q\_Depth}(\texttt{I}) < 40 \wedge \texttt{Q\_Depth}(\texttt{I}) \leq 1500$

then

act1 : $\texttt{Q\_Normal\_Status} := \texttt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$

Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(V5) $\geq$ 40 $\wedge$ Q_Depth(V5) $>$ 3000 $\wedge$
Q_Width(V6) $\geq$ 40 $\wedge$ Q_Depth(V6) $>$ 3000

grd5 : Q_Width(aVL) $\geq$ 40 $\wedge$ Q_Depth(aVL) $>$ 7000

grd6 : Q_Depth(I) $\geq$ 40 $\wedge$ Q_Depth(I) $>$ 1500

grd7 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_anterior_MI

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(II) $\geq$ 40 $\wedge$ Q_Depth(II) $>$ 3000 $\wedge$
Q_Width(III) $>$ 40 $\wedge$ Q_Depth(III) $>$ 7000 $\wedge$
Q_Width(aVF) $\geq$ 40 $\wedge$ Q_Depth(aVF) $>$ 3000

grd5 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_inferior_MI

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$
$\lor$
$\texttt{Disease\_step5} \in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$
$\lor$
$\texttt{Mice\_State} = \texttt{Exclude\_Mimics\_MI}$
$\lor$
$\texttt{Disease\_step2} = \texttt{LBBB}$

then

act1 : $\texttt{Age\_of\_Inf} :\in \{\texttt{recent}, \texttt{old}, \texttt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd2 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act1 : $\texttt{Disease\_step5} := \texttt{Hypertrophic\_cardiomyopathy}$

act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth}(\texttt{V1}) \geq 0 \land \texttt{R\_Depth}(\texttt{V1}) \leq 6000 \land \texttt{age} > 30$
1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth}(\texttt{V2}) > 200 \land \texttt{R\_Depth}(\texttt{V2}) \leq 12000$

grd3 : $\texttt{R\_Depth}(\texttt{V2}) \geq 1000 \land \texttt{R\_Depth}(\texttt{V2}) \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} :\in \{\texttt{late\_transition}, \texttt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$
R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{Q\_Wave\_State(V1)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V2)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V3)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V4)} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$

act2 : $\texttt{Mice\_State} := \texttt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$
R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\texttt{Q\_Wave\_State(V5)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V6)} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{lateral\_MI}, \texttt{Hypertrophic\_cardiomyopathy}\}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $(\texttt{P\_Wave\_Peak(II)} < 3000 \land$
$\texttt{P\_Wave\_Peak(V1)} < 3000)$
$\lor$
$(\texttt{P\_Wave\_Broad(II)} < 110 \land \texttt{P\_Wave\_Broad(V1)} < 110) \lor$
$\texttt{Diphasic(II)} = \texttt{FALSE} \lor$
$\texttt{Diphasic(V1)} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step6} := \texttt{NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{RAE}$

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

refines *P_Wave_assessment_Peaked_Yes_Check_RAE*

when

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Disease\_step6 = RAE$

grd4 : $Heart\_State = KO$

then

act1 : $Disease\_step6 := RV\_strain$

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \wedge \texttt{P\_Wave\_Broad(V1)} \geq 110) \vee$
$\texttt{Diphasic(II)} = \texttt{TRUE} \vee$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{LAE}$

end

Event *P_Wave_assessment_Broad_Yes_Check_LAE* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes_Check_LAE*

when

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \wedge \texttt{P\_Wave\_Broad(V1)} \geq 110) \vee$
$\texttt{Diphasic(II)} = \texttt{TRUE} \vee$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Disease\_step6} = \texttt{LAE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} :\in \{\texttt{mitral\_stenosis}, \texttt{mitral\_regurgitation}, \texttt{LV\_failure}, \texttt{dilated\_cardiomyopathy}\}$

end

Event *LVH_Assessment* $\widehat{=}$

LVH Assessment

refines *LVH_Assessment*

any

LVH_specificity specificity in percentage

sensitivity sensitivity in percentage

sex

where

grd1 : $(P\_Wave\_Broad(II) \geq 110 \wedge P\_Wave\_Broad(V1) \geq 110) \vee$
$Diphasic(II) = TRUE \vee$
$Diphasic(V1) = TRUE$

grd2 : $Disease\_step6 = LAE$

grd5 : $sex \in \{0, 1\}$
o for men and 1 for women

grd3 : $((S\_Depth(V1) + R\_Depth(V5)) > 35000$
$\vee$
$(S\_Depth(V1) + R\_Depth(V6)) > 35000)$
1mm = 1000 micrometer............. 1 assessment

grd4 : $((R\_Depth(aVL) + S\_Depth(V1) \geq 24000) \wedge sex = 0)$
$\vee$
$((R\_Depth(aVL) + S\_Depth(V1) \geq 18000) \wedge sex = 1)$
2 assessment

grd6 : $LVH\_specificity = 90$
$\wedge$
$sensitivity < 40$
1 and 2 assessment

grd7 : $Disease\_step6 = LAE \Rightarrow LVH\_specificity < 98$
3 assesssment

grd8 : $Heart\_State = KO$

grd9 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$
A : from step 8 development

then

act1 : $Disease\_step6 := LVH\_cause$

end

Event $RVH\_Assessment \ \widehat{=}$
RVH Assessment

refines $RVH\_Assessment$

any

age age od men or women
$aixs$ axis for deviation

where

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Disease\_step6 = RAE$

grd4 : $R\_Depth(V1) \geq 7000 \wedge age > 30$
1 assessment

grd5 : $S\_Depth(V5) \geq 7000 \vee$
$S\_Depth(V6) \geq 7000$
2 assessment

grd6 : $R\_S\_Ratio(V1) \geq 100$
R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment

grd7 : $R\_S\_Ratio(V5) \leq 100$
$\vee$
$R\_S\_Ratio(V6) \leq 100$
4 assessment

grd8 : $aixs \in 0 \,..\, 360 \wedge aixs \geq 110$
5 assessment

grd9 : $Disease\_step2 \notin \{LBBB, RBBB\}$
grd10 : $QRS\_Int < 120$
grd11 : $Heart\_State = KO$
grd12 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$
A : from step 8 development

then

act1 : $Disease\_step6 := RVH$

end

Event $T\_Wave\_Assessment\_Peaked\_V123456 \mathrel{\widehat{=}}$
T Wave Assessment

when

grd1 : $Heart\_State = KO$
grd2 : $\forall l \cdot l \in \{V1, V2, V3, V4, V5, V6\} \Rightarrow T\_Wave\_State(l) = Peaked$

then

act1 : $Disease\_step8 := Hyperkalemia$

end

Event $T\_Wave\_Assessment\_Peaked\_V12 \mathrel{\widehat{=}}$

refines $R\_Assessment\_Abnormal$

when

grd1 : $R\_Normal\_Status = FALSE$
grd2 : $T\_Wave\_State(V1) = Peaked \land$
$T\_Wave\_State(V2) = Peaked$

then

act1 : $Mice\_State := normal\_variant$

end

Event $T\_Wave\_Assessment\_Peaked\_V12\_MI \mathrel{\widehat{=}}$
posterior MI using T wave assessment in LEADS V1 and V2

when

grd1 : $T\_Wave\_State(V1) = Peaked \land$
$T\_Wave\_State(V2) = Peaked$
grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step8 := posterior\_MI$

end

Event $T\_Wave\_Assessment\_Flat \mathrel{\widehat{=}}$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Flat$
grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step8 := Nonspecific\_ST\_T\_changes$

end

Event $T\_Wave\_Assessment\_Inverted\_Yes \mathrel{\widehat{=}}$

when

$\texttt{grd1}:\ \forall l\cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$

$\texttt{grd2}:\ \forall l\cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE$

$\texttt{grd3}:\ Heart\_State = KO$

then

$\texttt{act1}:\ Disease\_step8 :\in \{Definite\_ischemia, Probable\_ischemia, Digitalis\_effect\}$

end

Event $T\_Wave\_Assessment\_Inverted\_No \mathrel{\widehat{=}}$

when

$\texttt{grd1}:\ \forall l\cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$

$\texttt{grd2}:\ \forall l\cdot l \in LEADS \Rightarrow ST\_elevation(l) = FALSE$
$\lor$
$Q\_Normal\_Status = TRUE$

$\texttt{grd3}:\ Heart\_State = KO$

then

$\texttt{act1}:\ Disease\_step8 := Nonspecific$

end

Event $T\_Wave\_Assessment\_Inverted\_Yes\_PM \mathrel{\widehat{=}}$

PM - pulmonary embolism this disease is already defined in previous development.

refines $P\_Wave\_assessment\_Peaked\_Yes\_Check\_RAE$

when

$\texttt{grd1}:\ P\_Wave\_Peak(II) \geq 3000$

$\texttt{grd2}:\ P\_Wave\_Peak(V1) \geq 3000$

$\texttt{grd3}:\ Disease\_step6 = RAE$

$\texttt{grd4}:\ Heart\_State = KO$

$\texttt{grd5}:\ (\forall t\cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

A : step 8

then

$\texttt{act1}:\ Disease\_step6 := pulmonary\_embolism$

end

END

An Event-B Specification of Step8_B_Ref
Generated Date: 25 Nov 2010 @ 03:39:38 PM

MACHINE Step8_B_Ref

REFINES Step8

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

`ST_seg_ele` ST segment for elevation 1mm=0.1mV

`Disease_step4`

`Q_Width` Q wave width

`Q_Depth` Q wave depth

`Q_Normal_Status` Q wave normal or abnormal

`Age_of_Inf` Age of Infarct

`Disease_step5`

`Mice_State`

`R_Depth` R wave depth or height (also use in Step 7)

`R_Normal_Status` R wave normal or abnormal

`Q_Wave_State` Q wave states for all LEADS

`P_Wave_Peak` function to estimate the peak of LEADS signal

`Disease_step6`

`Diphasic`

`PP_Interval`

`RR_Interval`

`P_Wave_Broad`

`S_Depth` S wave depth or height

R_S_Ratio   R wave and S wave Ratio function

T_Wave_State   T wave patterns...

Disease_step8

T_Wave_State_B   B for alternative method of T wave assessment

T_Normal_Status   T wave normal or abnormal

Abnormal_Shaped_ST

Asy_T_Inversion_strain   Asymmetric T wave Inversion strain pattern

T_inversion   Deep T wave inversion

T_inversion_l_d   T inversion Localized and Diffuse

Disease_step8_B

ST_depression

INVARIANTS

inv1 : $T\_Wave\_State\_B \in LEADS \to T\_State\_B$

inv2 : $T\_Normal\_Status \in BOOL$

inv3 : $Abnormal\_Shaped\_ST \in LEADS \to BOOL$

inv4 : $Asy\_T\_Inversion\_strain \in LEADS \to BOOL$

inv5 : $T\_inversion \in LEADS \to \mathbb{N}$

inv6 : $T\_inversion\_l\_d \in LEADS \to T\_State\_l\_d$

inv7 : $Disease\_step8\_B \in Disease\_states\_Codes\_step8B$

inv8 : $Sinus = Yes \wedge Disease\_step8 = Definite\_ischemia \Rightarrow Heart\_State = KO$

inv9 : $Sinus = Yes \wedge Disease\_step8 = Probable\_ischemia \Rightarrow Heart\_State = KO$

inv10 : $Sinus = Yes \wedge Disease\_step8\_B \in \{Cardiomyopathy, other\_nonspecific\}$
$\Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : RR_Int_equidistant :∈ LEADS → BOOL

act2 : PP_Int_equidistant :∈ LEADS → BOOL

act3 : P_Positive :∈ LEADS → BOOL

act4 : Sinus := No

act5 : PP_Interval :∈ LEADS → $\mathbb{N}$

act6 : RR_Interval :∈ LEADS → $\mathbb{N}$

act7 : Heart_Rate :∈ 1 .. 300

act8 : Heart_State := KO

act9 : PR_Int := 120

act10 : Disease_step2 := NDS2

act11 : QRS_Int := 50

act12 : Notched_R :∈ LEADS → BOOL

act13 : Small_R_QS :∈ LEADS → BOOL

act14 : Slurred_S_duration :∈ LEADS → $\mathbb{N}_1$

act15 : M_Shape_Complex :∈ LEADS → BOOL

act16 : Slurred_S :∈ LEADS → BOOL

act17 : ST_elevation :∈ LEADS → BOOL

act18 : Epsilon_Wave :∈ LEADS → BOOL

act19 : $\texttt{Delta\_Wave} := 0$
act20 : $\texttt{Disease\_step3} := \texttt{NDS3}$
act21 : $\texttt{ST\_seg\_ele} :\in \texttt{LEADS} \to \mathbb{N}$
act22 : $\texttt{Disease\_step4} := \texttt{NDS4}$
act57 : $\texttt{ST\_depression} :\in \texttt{LEADS} \to \mathbb{N}$
act23 : $\texttt{Q\_Width} :\in \texttt{LEADS} \to \mathbb{N}$
act24 : $\texttt{Q\_Depth} :\in \texttt{LEADS} \to \mathbb{N}$
act25 : $\texttt{Q\_Normal\_Status} := \texttt{FALSE}$
act26 : $\texttt{Mice\_State} := \texttt{NMS}$
act27 : $\texttt{R\_Depth} :\in \texttt{LEADS} \to \mathbb{N}$
act28 : $\texttt{R\_Normal\_Status} := \texttt{FALSE}$
act29 : $\texttt{Q\_Wave\_State} :\in \texttt{LEADS} \to \texttt{BOOL}$
act30 : $\texttt{Age\_of\_Inf} :\in \texttt{Age\_of\_Infarct}$
act31 : $\texttt{Disease\_step5} := \texttt{NDS5}$
act32 : $\texttt{Diphasic} :\in \texttt{LEADS} \to \texttt{BOOL}$
act33 : $\texttt{P\_Wave\_Broad} :\in \texttt{LEADS} \to \mathbb{N}$
act34 : $\texttt{P\_Wave\_Peak} :\in \texttt{LEADS} \to \mathbb{N}$
act35 : $\texttt{Disease\_step6} := \texttt{NDS6}$
act36 : $\texttt{S\_Depth} :\in \texttt{LEADS} \to \mathbb{N}$
act37 : $\texttt{R\_S\_Ratio} :\in \texttt{LEADS} \to \mathbb{N}$
act38 : $\texttt{T\_Wave\_State} :\in \texttt{LEADS} \to \texttt{T\_State}$
act39 : $\texttt{Disease\_step8} := \texttt{NDS8}$
act40 : $Abnormal\_Shaped\_ST :\in LEADS \to BOOL$
act41 : $Asy\_T\_Inversion\_strain :\in LEADS \to BOOL$
act43 : $T\_inversion\_l\_d :\in LEADS \to T\_State\_l\_d$
act42 : $T\_inversion :\in LEADS \to \mathbb{N}$
act44 : $Disease\_step8\_B := NDS8B$
act45 : $T\_Wave\_State\_B :\in LEADS \to T\_State\_B$
act46 : $T\_Normal\_Status := FALSE$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l}))$
$\land$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$

grd4 : $\texttt{rate} \in 60 \,..\, 100$
60..100 is the range of normal heart rate

grd5 : $\texttt{PR\_Int} \leq 200$
Heart is Normal if PR $\leq$ 200 `QRS_Int < 120`
$HeartisNormalifQRS < 120$

grd6grd7 : $\texttt{Disease\_step2} = \texttt{NDS2}$

grd8 : $\texttt{Disease\_step3} = \texttt{NDS3}$

grd9 : $\texttt{Disease\_step4} = \texttt{NDS4}$

grd10 : $\texttt{Disease\_step5} = \texttt{NDS5}$
grd11 : $\texttt{Disease\_step6} = \texttt{NDS6}$
grd12 : $\texttt{Disease\_step8} = \texttt{NDS8}$
grd13 : $Disease\_step8\_B = NDS8B$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$
act3 : $\texttt{Heart\_State} := \texttt{OK}$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall \texttt{l}\cdot \texttt{l} \in \{\texttt{II},\texttt{V1},\texttt{V2}\} \Rightarrow \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor \texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor \texttt{RR\_Interval}(\texttt{l}) \neq \texttt{PP\_Interval}(\texttt{l})) \lor \texttt{P\_Positive}(\texttt{II}) = \texttt{FALSE}$
grd2 : $\texttt{rate} \in 1 \,..\, 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$
act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists \texttt{l}\cdot \texttt{l} \in \{\texttt{II},\texttt{V1},\texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l})) \land \texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$
grd5 : $\texttt{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal
grd6 : $\texttt{Disease\_step3} = \texttt{WPW\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{Brugada\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{RV\_Dysplasia} \lor \texttt{Disease\_step3} = \texttt{IVCD}$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$
act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any
pr
where
grd1 : $\texttt{pr} \in 120 \,..\, 220$
time interval in (ms.)
grd2 : $\texttt{pr} > 200$
grd3 : $\texttt{Sinus} = \texttt{Yes}$
grd4 : $\texttt{Heart\_State} = \texttt{KO}$
then
act1 : $\texttt{PR\_Int} := \texttt{pr}$
act2 : $\texttt{Disease\_step2} := \texttt{First\_degree\_AV\_Block}$
end

Event *QRS_Test_LBBB* $\widehat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any
qrs
where
grd1 : $\texttt{qrs} \in 50 \,..\, 150$
grd2 : $\texttt{qrs} \geq 120$
grd3 : $\texttt{Sinus} = \texttt{Yes}$
grd4 : $\texttt{Heart\_State} = \texttt{KO}$
grd5 : $\texttt{Notched\_R}(\texttt{I}) = \texttt{TRUE} \land \texttt{Notched\_R}(\texttt{V5}) = \texttt{TRUE} \land \texttt{Notched\_R}(\texttt{V6}) = \texttt{TRUE}$
Right Bundle Branch Block (RBBB)
grd6 : $\texttt{Small\_R\_QS}(\texttt{V1}) = \texttt{TRUE} \land \texttt{Small\_R\_QS}(\texttt{V2}) = \texttt{TRUE}$
grd7 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \land \texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \land \texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \land \texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$
from step 5
grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$
from step 5
then
act1 : $\texttt{QRS\_Int} := \texttt{qrs}$
act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$
end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex(V1)} = \texttt{TRUE} \wedge$
$\texttt{M\_Shape\_Complex(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S(I)} = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S(V5)} = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S(V6)} = \texttt{TRUE}$

grd8 : $\texttt{Slurred\_S\_duration(I)} > 40 \wedge$
$\texttt{Slurred\_S\_duration(V5)} > 40 \wedge$
$\texttt{Slurred\_S\_duration(V6)} > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave
exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \vee \texttt{sympt} = \texttt{A\_LBBB}$

grd3 : $\texttt{d\_wave} \in \mathbb{N}$

grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$
Delta Wave + PR $\leq$ 120 Heart_State = KO

grd5grd6 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd7 : $\texttt{exmi} \in \texttt{Mice\_State5} \wedge \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act2 : $\texttt{Delta\_Wave} := \texttt{d\_wave}$

act3 : $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$
grd4 : $\texttt{Slurred\_S(V5)} = \texttt{FALSE} \land$
$\texttt{Slurred\_S(V6)} = \texttt{FALSE}$
grd5 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$
grd6 : $\texttt{ST\_elevation(V1)} = \texttt{TRUE} \land$
$\texttt{ST\_elevation(V2)} = \texttt{TRUE}$
grd7 : $\texttt{Sinus} = \texttt{Yes}$

then

act1 : $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$
grd2 : $\texttt{Heart\_State} = \texttt{KO}$
grd3 : $\texttt{QRS\_Int} \geq 110$
grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$
grd5 : $\texttt{Epsilon\_Wave(V1)} = \texttt{TRUE} \land$
$\texttt{Epsilon\_Wave(V3)} = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$
grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$
grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$
grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\mathtt{Disease\_step4} \in \{\mathtt{Acute\_inferior\_MI}, \mathtt{Acute\_anterior\_MI}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$

Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression}(\mathtt{l}) \geq 1000 \wedge \mathtt{ST\_depression}(\mathtt{k}) \geq 1000)$
$\wedge\, \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \in \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$

Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression}(\mathtt{l}) \geq 1000 \wedge \mathtt{ST\_depression}(\mathtt{k}) \geq 1000)$
$\wedge\, \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \notin \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

grd6 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$

grd7 : $T\_Normal\_Status = FALSE$

then

act1 : Disease_step4 := Ischemia

end

Event *Q_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : Q_Width(II) < 40 ∧ Q_Depth(II) ≤ 3000 ∧
Q_Width(aVF) < 40 ∧ Q_Depth(aVF) ≤ 3000 ∧
Q_Width(aVL) < 40

1000 micrometer= 1 milimeter

grd2 : Q_Width(III) ≤ 40 ∧ Q_Depth(III) ≤ 7000 ∧ Q_Depth(aVL) ≤ 7000

grd3 : Q_Depth(I) < 40 ∧ Q_Depth(I) ≤ 1500

then

act1 : Q_Normal_Status := TRUE

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$

Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000

grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000

grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500

grd7 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_anterior_MI

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(II) $\geq$ 40 $\wedge$ Q_Depth(II) $>$ 3000 $\wedge$
Q_Width(III) $>$ 40 $\wedge$ Q_Depth(III) $>$ 7000 $\wedge$
Q_Width(aVF) $\geq$ 40 $\wedge$ Q_Depth(aVF) $>$ 3000

grd5 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_inferior_MI

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : Disease_step4 = Acute_inferior_MI
$\vee$
Disease_step5 $\in$ {anterior_MI, LVH, emphysema}
$\vee$
Mice_State = Exclude_Mimics_MI
$\vee$
Disease_step2 = LBBB

then

act1 : Age_of_Inf :$\in$ {recent, old, indeterminate}

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : Disease_step4 = Acute_inferior_MI

grd2 : exmi $\in$ Mice_State5 $\wedge$ exmi = Exclude_Mimics_MI

then

act1 : Disease_step5 := Hypertrophic_cardiomyopathy act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth(V1)} \geq 0 \land \texttt{R\_Depth(V1)} \leq 6000 \land \texttt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth(V2)} > 200 \land \texttt{R\_Depth(V2)} \leq 12000$

grd3 : $\texttt{R\_Depth(V2)} \geq 1000 \land \texttt{R\_Depth(V2)} \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} :\in \{\texttt{late\_transition}, \texttt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{Q\_Wave\_State(V1)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V2)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V3)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V4)} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$

act2 : $\texttt{Mice\_State} := \texttt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\texttt{Q\_Wave\_State(V5)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V6)} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\mathtt{Disease\_step5} :\in \{\mathtt{lateral\_MI}, \mathtt{Hypertrophic\_cardiomyopathy}\}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $(\mathtt{P\_Wave\_Peak}(\mathtt{II}) < 3000 \wedge$
$\mathtt{P\_Wave\_Peak}(\mathtt{V1}) < 3000)$
$\vee$
$(\mathtt{P\_Wave\_Broad}(\mathtt{II}) < 110 \wedge \mathtt{P\_Wave\_Broad}(\mathtt{V1}) < 110) \vee$
$\mathtt{Diphasic}(\mathtt{II}) = \mathtt{FALSE} \vee$
$\mathtt{Diphasic}(\mathtt{V1}) = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : $\mathtt{P\_Wave\_Peak}(\mathtt{II}) \geq 3000$
grd2 : $\mathtt{P\_Wave\_Peak}(\mathtt{V1}) \geq 3000$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RAE}$

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes_Check_RAE*

when

grd1 : $\mathtt{P\_Wave\_Peak}(\mathtt{II}) \geq 3000$
grd2 : $\mathtt{P\_Wave\_Peak}(\mathtt{V1}) \geq 3000$
grd3 : $\mathtt{Disease\_step6} = \mathtt{RAE}$
grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RV\_strain}$

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : $(\mathtt{P\_Wave\_Broad}(\mathtt{II}) \geq 110 \wedge \mathtt{P\_Wave\_Broad}(\mathtt{V1}) \geq 110) \vee$
$\mathtt{Diphasic}(\mathtt{II}) = \mathtt{TRUE} \vee$
$\mathtt{Diphasic}(\mathtt{V1}) = \mathtt{TRUE}$
grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{LAE}$

end

Event $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE \widehat{=}$

extends $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE$

when

grd1 : $(\mathtt{P\_Wave\_Broad(II)} \geq 110 \wedge \mathtt{P\_Wave\_Broad(V1)} \geq 110) \vee$
$\mathtt{Diphasic(II)} = \mathtt{TRUE} \vee$
$\mathtt{Diphasic(V1)} = \mathtt{TRUE}$

grd2 : $\mathtt{Disease\_step6} = \mathtt{LAE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} :\in \{\mathtt{mitral\_stenosis}, \mathtt{mitral\_regurgitation}, \mathtt{LV\_failure}, \mathtt{dilated\_cardiomyopathy}\}$

end

Event $LVH\_Assessment \widehat{=}$

LVH Assessment

refines $LVH\_Assessment$

any

$LVH\_specificity$ specificity in percentage

$sensitivity$ sensitivity in percentage

sex

where

grd1 : $(P\_Wave\_Broad(II) \geq 110 \wedge P\_Wave\_Broad(V1) \geq 110) \vee$
$Diphasic(II) = TRUE \vee$
$Diphasic(V1) = TRUE$

grd2 : $Disease\_step6 = LAE$

grd5 : $sex \in \{0, 1\}$

o for men and 1 for women

grd3 : $((S\_Depth(V1) + R\_Depth(V5)) > 35000$
$\vee$
$(S\_Depth(V1) + R\_Depth(V6)) > 35000)$

1mm = 1000 micrometer............. 1 assessment

grd4 : $((R\_Depth(aVL) + S\_Depth(V1) \geq 24000) \wedge sex = 0)$
$\vee$
$((R\_Depth(aVL) + S\_Depth(V1) \geq 18000) \wedge sex = 1)$

2 assessment

grd6 : $LVH\_specificity = 90$
$\wedge$
$sensitivity < 40$

1 and 2 assessment

grd7 : $Disease\_step6 = LAE \Rightarrow LVH\_specificity < 98$

3 assesssment

grd8 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

A or B : from step 8 development

grd9 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$

$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd10 : $Asy\_T\_Inversion\_strain(V5) = TRUE \wedge$
$Asy\_T\_Inversion\_strain(V6) = TRUE \wedge$
$Asy\_T\_Inversion\_strain(V4) = TRUE$

grd11 : $Heart\_State = KO$

grd12 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step6 := LVH\_cause$

end

Event $RVH\_Assessment \widehat{=}$
RVH Assessment

refines $RVH\_Assessment$

any

age age od men or women
aixs axis for deviation

where

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Disease\_step6 = RAE$

grd4 : $R\_Depth(V1) \geq 7000 \wedge age > 30$
1 assessment

grd5 : $S\_Depth(V5) \geq 7000 \vee$
$S\_Depth(V6) \geq 7000$
2 assessment

grd6 : $R\_S\_Ratio(V1) \geq 100$
R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment

grd7 : $R\_S\_Ratio(V5) \leq 100$
$\vee$
$R\_S\_Ratio(V6) \leq 100$
4 assessment

grd8 : $aixs \in 0 \mathrel{..} 360 \wedge aixs \geq 110$
5 assessment

grd9 : $Disease\_step2 \notin \{LBBB, RBBB\}$

grd10 : $QRS\_Int < 120$

grd11 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

$AorB : fromstep8development$
$\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd12grd13 : $Asy\_T\_Inversion\_strain(V1) = TRUE \wedge$
$Asy\_T\_Inversion\_strain(V2) = TRUE \wedge$
$Asy\_T\_Inversion\_strain(V3) = TRUE$

grd14 : $Heart\_State = KO$

grd15 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step6 := RVH$

end

Event $T\_Wave\_Assessment\_Peaked\_V123456 \widehat{=}$
T Wave Assessment

extends $T\_Wave\_Assessment\_Peaked\_V123456$

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{V1}, \mathtt{V2}, \mathtt{V3}, \mathtt{V4}, \mathtt{V5}, \mathtt{V6}\} \Rightarrow \mathtt{T\_Wave\_State(l)} = \mathtt{Peaked}$

then

act1 : $\mathtt{Disease\_step8} := \mathtt{Hyperkalemia}$

end

Event $T\_Wave\_Assessment\_Peaked\_V12 \widehat{=}$

refines $T\_Wave\_Assessment\_Peaked\_V12$

when

grd1 : $R\_Normal\_Status = FALSE$

grd2 : $T\_Wave\_State(V1) = Peaked \wedge$
$T\_Wave\_State(V2) = Peaked$

grd3 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd4 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$
step 8 B

grd5 : $T\_Normal\_Status = FALSE$

then

act1 : $Mice\_State := normal\_variant$

end

Event $T\_Wave\_Assessment\_Peaked\_V12\_MI \widehat{=}$
posterior MI using T wave assessment in LEADS V1 and V2

refines $T\_Wave\_Assessment\_Peaked\_V12\_MI$

when

grd1 : $T\_Wave\_State(V1) = Peaked \wedge$
$T\_Wave\_State(V2) = Peaked$

grd6 : $Heart\_State = KO$

grd2 : $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$

grd4 : $T\_inversion\_l\_d(V2) = Localized \wedge$
$T\_inversion\_l\_d(V3) = Localized \wedge$
$T\_inversion\_l\_d(V4) = Localized \wedge$
$T\_inversion\_l\_d(V5) = Localized$

grd5 : $T\_inversion\_l\_d(II) = Localized \wedge$
$T\_inversion\_l\_d(III) = Localized \wedge$
$T\_inversion\_l\_d(aVF) = Localized$

grd7 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8 := posterior\_MI$

end

Event $T\_Wave\_Assessment\_Flat \ \widehat{=}$

refines $T\_Wave\_Assessment\_Flat$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Flat$

grd4 : $Heart\_State = KO$

grd2 : $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

step 8 B

grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$

grd5 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8 := Nonspecific\_ST\_T\_changes$

act2 : $Disease\_step8\_B :\in \{Cardiomyopathy, Electrolyte\_depletion, Alcohol, Myocarditis, Other\}$

end

Event $T\_Wave\_Assessment\_Inverted\_Yes \ \widehat{=}$

extends $T\_Wave\_Assessment\_Inverted\_Yes$

when

grd1 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State(l)} = \mathtt{Inverted}$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation(l)} = \mathtt{TRUE}$
$\vee$
$\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : Disease_step8 :∈ {Definite_ischemia, Probable_ischemia, Digitalis_effect}

end

Event *T_Wave_Assessment_Inverted_No* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_No*

when

grd1 : $\forall$l·l $\in$ LEADS $\Rightarrow$ T_Wave_State(l) = Inverted

grd2 : $\forall$l·l $\in$ LEADS $\Rightarrow$ ST_elevation(l) = FALSE
$\lor$
Q_Normal_Status = TRUE

grd3 : Heart_State = KO

then

act1 : Disease_step8 := Nonspecific

end

Event *T_Wave_Assessment_Inverted_Yes_PM* $\widehat{=}$

PM - pulmonary embolism this disease is already defined in previous development.

refines *T_Wave_Assessment_Inverted_Yes_PM*

when

grd1 : $P\_Wave\_Peak(II) \geq 3000$

grd2 : $P\_Wave\_Peak(V1) \geq 3000$

grd3 : $Disease\_step6 = RAE$

grd4 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

$A : step8\ Heart\_State = KO$

grd7grd5 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$(ST\_elevation(l1) = FALSE \land ST\_elevation(k1) = FALSE)$
$\land$
$((ST\_seg\_ele(l1) < 1000 \land ST\_seg\_ele(k1) < 1000)$
$\lor$
$(Abnormal\_Shaped\_ST(l1) = FALSE \land Abnormal\_Shaped\_ST(k1) = FALSE))$
$\Rightarrow l1 \neq k1))$

grd6 : $Asy\_T\_Inversion\_strain(V1) = TRUE \land$
$Asy\_T\_Inversion\_strain(V2) = TRUE \land$
$Asy\_T\_Inversion\_strain(V3) = TRUE$

grd8 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step6 := pulmonary\_embolism$

end

Event *T_Wave_Assessment_B* $\widehat{=}$

B for alternate method of T wave assessment

when

grd1 : $\forall l \cdot l \in \{I, II, V3, V4, V5, V6\} \Rightarrow T\_Wave\_State\_B(l) = Upright$

grd2 : $T\_Wave\_State\_B(aVL) = Inverted\_B$

grd3 : $\forall l \cdot l \in \{III, aVL, aVF, V1, V2\} \Rightarrow T\_Wave\_State\_B(l) = Variable$

then

act1 : $T\_Normal\_Status := TRUE$

end

Event $T\_Wave\_Assessment\_B\_DI \mathrel{\widehat=}$
abnormal T wave .....in B ...DI(Definite Ischemia)

refines $T\_Wave\_Assessment\_Inverted\_Yes$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$

grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE$

grd3 : $T\_Normal\_Status = FALSE$
added in step-8 B

grd5 : $Heart\_State = KO$

grd4 : $\exists l, k \cdot l \in LEADS \land k \in LEADS \land$
$((ST\_seg\_ele(l) \geq 1000 \land ST\_seg\_ele(k) \geq 1000) \lor$
$(ST\_elevation(l) = TRUE \land ST\_elevation(k) = TRUE)$
$\lor$
$(Abnormal\_Shaped\_ST(l) = TRUE \land Abnormal\_Shaped\_ST(k) = TRUE))$
$\land$
$l \neq k$
added in step-8 B

then

act1 : $Disease\_step8 := Definite\_ischemia$

end

Event $T\_Inversion\_Likely\_Ischemia \mathrel{\widehat=}$
probable Ischemia or Likly ischemia

refines $T\_Wave\_Assessment\_Inverted\_Yes$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$

grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE$

grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$
1 mm= 1000

grd4 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd5 : $T\_inversion\_l\_d(V2) = Localized \land$
$T\_inversion\_l\_d(V3) = Localized \land$
$T\_inversion\_l\_d(V4) = Localized \land$
$T\_inversion\_l\_d(V5) = Localized$

grd6 : $T\_inversion\_l\_d(II) = Localized \land$
$T\_inversion\_l\_d(III) = Localized \land$
$T\_inversion\_l\_d(aVF) = Localized$

b. of Deep inversion ¿ 5mm

grd7 : $Heart\_State = KO$
grd8 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8 := Probable\_ischemia$

end

Event $T\_Inversion\_Diffuse\_B \;\widehat{=}$

Step 8 B for c.

when

grd1 : $\lor$

$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd2 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$
grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion\_l\_d(l) = Diffuse$
grd4 : $Heart\_State = KO$
grd5 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8\_B :\in \{Cardiomyopathy, other\_nonspecific\}$

end

END

An Event-B Specification of Step9
Generated Date: 25 Nov 2010 @ 03:38:45 PM

CONTEXT Step9

SETS

`QRS_directions`

`Axis_deviation`

`Disease_Codes_Step9`

CONSTANTS

`D_Upright`

`D_Positive`

`D_Negative`

`LAD`

`RAD`

`ND`

`LAFB` LAFB (hemiblock)

`MSCHD` Mechanical shifts causing a horizontal heart; high diaphragm; preg- nancy, ascites

`Some_Form_VT`

`ED_OC` Endocardial cushion defects and other congenital heart disease

`LPFB`

`Dextrocardia`

`NV_MSEC` Normal variants: mechanical shifts or emphysema causing a vertical heart

`NDS9`

AXIOMS

axm1 : $QRS\_directions = \{D\_Upright, D\_Positive, D\_Negative\}$

axm2 : $\neg D\_Upright = D\_Positive$

axm3 : $\neg D\_Upright = D\_Negative$

axm4 : $\neg D\_Positive = D\_Negative$

axm5 : $Axis\_deviation = \{LAD, RAD, ND\}$

axm6 : $\neg LAD = RAD$

axm7 : $\neg LAD = ND$

axm8 : $\neg RAD = ND$

axm9 : $Disease\_Codes\_Step9 = \{LAFB, MSCHD, Some\_Form\_VT, ED\_OC, LPFB, Dextrocardia, NV\_MSEC, NDS9\}$

axm10 : $\neg LAFB = MSCHD$

axm11 : $\neg LAFB = Some\_Form\_VT$

axm12 : $\neg LAFB = ED\_OC$

axm13 : $\neg LAFB = LPFB$

axm14 : $\neg LAFB = Dextrocardia$

axm15 : $\neg LAFB = NV\_MSEC$

axm16 : $\neg LAFB = NDS9$

axm17 : $\neg MSCHD = Some\_Form\_VT$

axm18 : $\neg MSCHD = ED\_OC$

$\texttt{axm19}: \neg MSCHD = LPFB$

$\texttt{axm20}: \neg MSCHD = Dextrocardia$

$\texttt{axm21}: \neg MSCHD = NV\_MSEC$

$\texttt{axm22}: \neg MSCHD = NDS9$

$\texttt{axm23}: \neg Some\_Form\_VT = ED\_OC$

$\texttt{axm24}: \neg Some\_Form\_VT = LPFB$

$\texttt{axm25}: \neg Some\_Form\_VT = Dextrocardia$

$\texttt{axm26}: \neg Some\_Form\_VT = NV\_MSEC$

$\texttt{axm27}: \neg Some\_Form\_VT = NDS9$

$\texttt{axm28}: \neg ED\_OC = LPFB$

$\texttt{axm29}: \neg ED\_OC = Dextrocardia$

$\texttt{axm30}: \neg ED\_OC = NV\_MSEC$

$\texttt{axm31}: \neg ED\_OC = NDS9$

$\texttt{axm32}: \neg LPFB = Dextrocardia$

$\texttt{axm33}: \neg LPFB = NV\_MSEC$

$\texttt{axm34}: \neg LPFB = NDS9$

$\texttt{axm35}: \neg Dextrocardia = NV\_MSEC$

$\texttt{axm36}: \neg Dextrocardia = NDS9$

$\texttt{axm37}: \neg NV\_MSEC = NDS9$

END

An Event-B Specification of Step9_Axis_Assessment
Generated Date: 25 Nov 2010 @ 03:39:41 PM

MACHINE Step9_Axis_Assessment

REFINES Step8_B_Ref

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

`ST_seg_ele` ST segment for elevation 1mm=0.1mV

`Disease_step4`

`Q_Width` Q wave width

`Q_Depth` Q wave depth

`Q_Normal_Status` Q wave normal or abnormal

`Age_of_Inf` Age of Infarct

`Disease_step5`

`Mice_State`

`R_Depth` R wave depth or height (also use in Step 7)

`R_Normal_Status` R wave normal or abnormal

`PP_Interval`

`RR_Interval`

`Q_Wave_State` Q wave states for all LEADS

`P_Wave_Peak` function to estimate the peak of LEADS signal

`Disease_step6`

`Diphasic`

`P_Wave_Broad`

`S_Depth` S wave depth or height

R_S_Ratio R wave and S wave Ratio function

T_Wave_State T wave patterns...

Disease_step8

T_Wave_State_B B for alternative method of T wave assessment

T_Normal_Status T wave normal or abnormal

Abnormal_Shaped_ST

Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern

T_inversion Deep T wave inversion

T_inversion_l_d T inversion Localized and Diffuse

Disease_step8_B

QRS_Axis_State QRS Axis Direction

minAngle min. value of angle of Axis in degree

maxAngle max. value of angle of Axis in degree

ST_depression

INVARIANTS

inv1 : $QRS\_Axis\_State \in LEADS \rightarrow QRS\_directions$

inv2 : $minAngle \in -90 \,..\, 180$

inv3 : $maxAngle \in -90 \,..\, 180$

EVENTS

Initialisation

extended

begin

act1 : RR_Int_equidistant :∈ LEADS → BOOL
act2 : PP_Int_equidistant :∈ LEADS → BOOL
act3 : P_Positive :∈ LEADS → BOOL
act4 : Sinus := No
act5 : PP_Interval :∈ LEADS → ℕ
act6 : RR_Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → $\mathbb{N}_1$
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ

act23 : $\texttt{Q\_Width} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act24 : $\texttt{Q\_Depth} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act25 : $\texttt{Q\_Normal\_Status} := \texttt{FALSE}$

act26 : $\texttt{Mice\_State} := \texttt{NMS}$

act27 : $\texttt{R\_Depth} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act28 : $\texttt{R\_Normal\_Status} := \texttt{FALSE}$

act29 : $\texttt{Q\_Wave\_State} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act30 : $\texttt{Age\_of\_Inf} :\in \texttt{Age\_of\_Infarct}$

act31 : $\texttt{Disease\_step5} := \texttt{NDS5}$

act32 : $\texttt{Diphasic} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act33 : $\texttt{P\_Wave\_Broad} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act34 : $\texttt{P\_Wave\_Peak} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act35 : $\texttt{Disease\_step6} := \texttt{NDS6}$

act36 : $\texttt{S\_Depth} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act37 : $\texttt{R\_S\_Ratio} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act38 : $\texttt{T\_Wave\_State} :\in \texttt{LEADS} \rightarrow \texttt{T\_State}$

act39 : $\texttt{Disease\_step8} := \texttt{NDS8}$

act40 : $\texttt{Abnormal\_Shaped\_ST} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act41 : $\texttt{Asy\_T\_Inversion\_strain} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$

act43 : $\texttt{T\_inversion\_l\_d} :\in \texttt{LEADS} \rightarrow \texttt{T\_State\_l\_d}$

act42 : $\texttt{T\_inversion} :\in \texttt{LEADS} \rightarrow \mathbb{N}$

act44 : $\texttt{Disease\_step8\_B} := \texttt{NDS8B}$

act45 : $\texttt{T\_Wave\_State\_B} :\in \texttt{LEADS} \rightarrow \texttt{T\_State\_B}$

act46 : $\texttt{T\_Normal\_Status} := \texttt{FALSE}$

act47 : $QRS\_Axis\_State :\in LEADS \rightarrow QRS\_directions$

act48 : $minAngle := 0$

act49 : $maxAngle := 0$

end

Event *Rhythm_test_TRUE* $\widehat{=}$

Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l}))$
$\land$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$

grd4 : $\texttt{rate} \in 60 \,..\, 100$

60..100 is the range of normal heart rate

grd5 : $\texttt{PR\_Int} \leq 200$

Heart is Normal if PR ≤ 200 `QRS_Int < 120`

$HeartisNormalifQRS < 120$

grd6grd7 : $\texttt{Disease\_step2} = \texttt{NDS2}$

grd8 : $\texttt{Disease\_step3} = \texttt{NDS3}$

grd9 : $\texttt{Disease\_step4} = \texttt{NDS4}$

grd10 : $\texttt{Disease\_step5} = \texttt{NDS5}$

grd11 : $\texttt{Disease\_step6} = \texttt{NDS6}$

grd12 : $\texttt{Disease\_step8} = \texttt{NDS8}$
grd13 : $\texttt{Disease\_step8\_B} = \texttt{NDS8B}$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$
act3 : $\texttt{Heart\_State} := \texttt{OK}$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor$
$\texttt{RR\_Interval}(\texttt{l}) \neq \texttt{PP\_Interval}(\texttt{l}))$
$\lor$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{FALSE}$
grd2 : $\texttt{rate} \in 1 \mathinner{..} 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$
act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l}))$
$\land$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$
grd5 : $\texttt{rate} \in 1 \mathinner{..} 300 \setminus 60 \mathinner{..} 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal
grd6 : $\texttt{Disease\_step3} = \texttt{WPW\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{Brugada\_Syndrome} \lor$
$\texttt{Disease\_step3} = \texttt{RV\_Dysplasia} \lor \texttt{Disease\_step3} = \texttt{IVCD}$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$
act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $pr \in 120 .. 220$

time interval in (ms.)

grd2 : $pr > 200$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

then

act1 : $PR\_Int := pr$

act2 : $Disease\_step2 := First\_degree\_AV\_Block$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $qrs \in 50 .. 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $Notched\_R(I) = TRUE \land$
$Notched\_R(V5) = TRUE \land$
$Notched\_R(V6) = TRUE$

Right Bundle Branch Block (RBBB)

grd6 : $Small\_R\_QS(V1) = TRUE \land$
$Small\_R\_QS(V2) = TRUE$

grd7 : $Q\_Wave\_State(V1) = TRUE \land$
$Q\_Wave\_State(V2) = TRUE \land$
$Q\_Wave\_State(V3) = TRUE \land$
$Q\_Wave\_State(V4) = TRUE$

from step 5

grd8 : $R\_Normal\_Status = FALSE$

from step 5

then

act1 : $QRS\_Int := qrs$

act2 : $Disease\_step2 := LBBB$

end

Event *QRS_Test_RBBB* $\widehat{=}$

Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : qrs ∈ 50 .. 150
grd2 : qrs ≥ 120
grd3 : Sinus = Yes
grd4 : Heart_State = KO
grd5 : M_Shape_Complex(V1) = TRUE ∧
    M_Shape_Complex(V2) = TRUE
grd7 : Slurred_S(I) = TRUE ∧
    Slurred_S(V5) = TRUE ∧
    Slurred_S(V6) = TRUE
grd8 : Slurred_S_duration(I) > 40 ∧
    Slurred_S_duration(V5) > 40 ∧
    Slurred_S_duration(V6) > 40

then

act1 : QRS_Int := qrs
act2 : Disease_step2 := RBBB

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* ≙
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave
exmi

where

grd1 : QRS_Int ≥ 110
grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
grd3 : d_wave ∈ ℕ
grd4 : (d_wave + PR_Int) ≤ 120
  Delta Wave + PR ≤ 120 Heart_State = KO
grd5grd6 : Disease_step4 = Acute_inferior_MI
grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI

then

act2 : Delta_Wave := d_wave
act3 : Disease_step3 := WPW_Syndrome

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* ≙
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int ≥ 110
grd4 : Slurred_S(V5) = FALSE ∧
    Slurred_S(V6) = FALSE

grd5 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, NDS3\}$
grd6 : $ST\_elevation(V1) = TRUE \land$
$ST\_elevation(V2) = TRUE$
grd7 : $Sinus = Yes$

then

act1 : $Disease\_step3 := Brugada\_Syndrome$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : $sympt = A\_RBBB$
grd2 : $Heart\_State = KO$
grd3 : $QRS\_Int \geq 110$
grd4 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, Brugada\_Syndrome, NDS3\}$
grd5 : $Epsilon\_Wave(V1) = TRUE \land$
$Epsilon\_Wave(V3) = TRUE$

then

act1 : $Disease\_step3 := RV\_Dysplasia$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $QRS\_Int \geq 110$
grd2 : $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, Brugada\_Syndrome, RV\_Dysplasia, NDS3\}$
grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step3 := IVCD$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $Heart\_State = KO$
grd2 : $Sinus = Yes$

grd3 : $\vee$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\mathtt{Disease\_step4} \in \{\mathtt{Acute\_inferior\_MI}, \mathtt{Acute\_anterior\_MI}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$
Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression(l)} \geq 1000 \wedge \mathtt{ST\_depression(k)} \geq 1000)$
$\wedge\, \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \in \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$
Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression(l)} \geq 1000 \wedge \mathtt{ST\_depression(k)} \geq 1000)$
$\wedge\, \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \notin \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

grd6 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion(l)} < 5000$

grd7 : T_Normal_Status = FALSE

then

act1 : Disease_step4 := Ischemia

end

Event *Q_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : Q_Width(II) < 40 ∧ Q_Depth(II) ≤ 3000 ∧
Q_Width(aVF) < 40 ∧ Q_Depth(aVF) ≤ 3000 ∧
Q_Width(aVL) < 40

1000 micrometer= 1 milimeter

grd2 : Q_Width(III) ≤ 40 ∧ Q_Depth(III) ≤ 7000 ∧ Q_Depth(aVL) ≤ 7000

grd3 : Q_Depth(I) < 40 ∧ Q_Depth(I) ≤ 1500

then

act1 : Q_Normal_Status := TRUE

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$

Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : ∨

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000

grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000

grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500

grd7 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_anterior_MI

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\text{Q\_Width(II)} \geq 40 \wedge \text{Q\_Depth(II)} > 3000 \wedge$
$\text{Q\_Width(III)} > 40 \wedge \text{Q\_Depth(III)} > 7000 \wedge$
$\text{Q\_Width(aVF)} \geq 40 \wedge \text{Q\_Depth(aVF)} > 3000$

grd5 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_inferior_MI

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : Disease_step4 = Acute_inferior_MI
$\vee$
Disease_step5 $\in$ {anterior_MI, LVH, emphysema}
$\vee$
Mice_State = Exclude_Mimics_MI
$\vee$
Disease_step2 = LBBB

then

act1 : Age_of_Inf :$\in$ {recent, old, indeterminate}

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : Disease_step4 = Acute_inferior_MI

grd2 : exmi $\in$ Mice_State5 $\wedge$ exmi = Exclude_Mimics_MI

then

act1 : Disease_step5 := Hypertrophic_cardiomyopathy act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth}(\texttt{V1}) \geq 0 \wedge \texttt{R\_Depth}(\texttt{V1}) \leq 6000 \wedge \texttt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth}(\texttt{V2}) > 200 \wedge \texttt{R\_Depth}(\texttt{V2}) \leq 12000$

grd3 : $\texttt{R\_Depth}(\texttt{V2}) \geq 1000 \wedge \texttt{R\_Depth}(\texttt{V2}) \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} :\in \{\texttt{late\_transition}, \texttt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$

act2 : $\texttt{Mice\_State} := \texttt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\texttt{Q\_Wave\_State}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V6}) = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{lateral\_MI}, \texttt{Hypertrophic\_cardiomyopathy}\}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $(\texttt{P\_Wave\_Peak}(\texttt{II}) < 3000 \land$
$\texttt{P\_Wave\_Peak}(\texttt{V1}) < 3000)$
$\lor$
$(\texttt{P\_Wave\_Broad}(\texttt{II}) < 110 \land \texttt{P\_Wave\_Broad}(\texttt{V1}) < 110) \lor$
$\texttt{Diphasic}(\texttt{II}) = \texttt{FALSE} \lor$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step6} := \texttt{NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : $\texttt{P\_Wave\_Peak}(\texttt{II}) \geq 3000$
grd2 : $\texttt{P\_Wave\_Peak}(\texttt{V1}) \geq 3000$
grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{RAE}$

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes_Check_RAE*

when

grd1 : $\texttt{P\_Wave\_Peak}(\texttt{II}) \geq 3000$
grd2 : $\texttt{P\_Wave\_Peak}(\texttt{V1}) \geq 3000$
grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$
grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{RV\_strain}$

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : $(\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \land \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \lor$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \lor$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$
grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{LAE}$

end

Event $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE \;\widehat{=}$

extends $P\_Wave\_assessment\_Broad\_Yes\_Check\_LAE$

when

grd1 : $(\mathtt{P\_Wave\_Broad}(\mathtt{II}) \geq 110 \land \mathtt{P\_Wave\_Broad}(\mathtt{V1}) \geq 110) \lor$
$\mathtt{Diphasic}(\mathtt{II}) = \mathtt{TRUE} \lor$
$\mathtt{Diphasic}(\mathtt{V1}) = \mathtt{TRUE}$

grd2 : $\mathtt{Disease\_step6} = \mathtt{LAE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} :\in \{\mathtt{mitral\_stenosis}, \mathtt{mitral\_regurgitation}, \mathtt{LV\_failure}, \mathtt{dilated\_cardiomyopathy}\}$

end

Event $LVH\_Assessment \;\widehat{=}$

LVH Assessment

extends $LVH\_Assessment$

any

$\mathtt{LVH\_specificity}$ specificity in percentage

$\mathtt{sensitivity}$ sensitivity in percentage

$\mathtt{sex}$

where

grd1 : $(\mathtt{P\_Wave\_Broad}(\mathtt{II}) \geq 110 \land \mathtt{P\_Wave\_Broad}(\mathtt{V1}) \geq 110) \lor$
$\mathtt{Diphasic}(\mathtt{II}) = \mathtt{TRUE} \lor$
$\mathtt{Diphasic}(\mathtt{V1}) = \mathtt{TRUE}$

grd2 : $\mathtt{Disease\_step6} = \mathtt{LAE}$

grd5 : $\mathtt{sex} \in \{0, 1\}$

o for men and 1 for women

grd3 : $((\mathtt{S\_Depth}(\mathtt{V1}) + \mathtt{R\_Depth}(\mathtt{V5})) > 35000$
$\lor$
$(\mathtt{S\_Depth}(\mathtt{V1}) + \mathtt{R\_Depth}(\mathtt{V6})) > 35000)$

1mm = 1000 micrometer............. 1 assessment

grd4 : $((\mathtt{R\_Depth}(\mathtt{aVL}) + \mathtt{S\_Depth}(\mathtt{V1}) \geq 24000) \land \mathtt{sex} = 0)$
$\lor$
$((\mathtt{R\_Depth}(\mathtt{aVL}) + \mathtt{S\_Depth}(\mathtt{V1}) \geq 18000) \land \mathtt{sex} = 1)$

2 assessment

grd6 : $\mathtt{LVH\_specificity} = 90$
$\land$
$\mathtt{sensitivity} < 40$

1 and 2 assessment

grd7 : $\mathtt{Disease\_step6} = \mathtt{LAE} \Rightarrow \mathtt{LVH\_specificity} < 98$

3 assesssment

grd8 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

A or B : from step 8 development

grd9 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$

$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd10 : $\mathtt{Asy\_T\_Inversion\_strain(V5) = TRUE} \wedge$
$\mathtt{Asy\_T\_Inversion\_strain(V6) = TRUE} \wedge$
$\mathtt{Asy\_T\_Inversion\_strain(V4) = TRUE}$

grd11 : $\mathtt{Heart\_State = KO}$

grd12 : $\mathtt{T\_Normal\_Status = FALSE}$

then

act1 : $\mathtt{Disease\_step6 := LVH\_cause}$

end

Event $RVH\_Assessment \mathrel{\widehat{=}}$
RVH Assessment

extends $RVH\_Assessment$

any

age age od men or women

aixs axis for deviation

where

grd1 : $\mathtt{P\_Wave\_Peak(II) \geq 3000}$

grd2 : $\mathtt{P\_Wave\_Peak(V1) \geq 3000}$

grd3 : $\mathtt{Disease\_step6 = RAE}$

grd4 : $\mathtt{R\_Depth(V1) \geq 7000 \wedge age > 30}$
1 assessment

grd5 : $\mathtt{S\_Depth(V5) \geq 7000} \vee$
$\mathtt{S\_Depth(V6) \geq 7000}$
2 assessment

grd6 : $\mathtt{R\_S\_Ratio(V1) \geq 100}$
R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment

grd7 : $\mathtt{R\_S\_Ratio(V5) \leq 100}$
$\vee$
$\mathtt{R\_S\_Ratio(V6) \leq 100}$
4 assessment

grd8 : $\mathtt{aixs \in 0 \,..\, 360 \wedge aixs \geq 110}$
5 assessment

grd9 : $\mathtt{Disease\_step2 \notin \{LBBB, RBBB\}}$

grd10 : $\mathtt{QRS\_Int < 120}$

grd11 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

$AorB : fromstep8development$
$\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd12grd13 : $\texttt{Asy\_T\_Inversion\_strain(V1)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V2)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V3)} = \texttt{TRUE}$

grd14 : $\texttt{Heart\_State} = \texttt{KO}$

grd15 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step6} := \texttt{RVH}$

end

Event *T_Wave_Assessment_Peaked_V123456* $\widehat{=}$
T Wave Assessment

extends *T_Wave_Assessment_Peaked_V123456*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{V1}, \texttt{V2}, \texttt{V3}, \texttt{V4}, \texttt{V5}, \texttt{V6}\} \Rightarrow \texttt{T\_Wave\_State(l)} = \texttt{Peaked}$

then

act1 : $\texttt{Disease\_step8} := \texttt{Hyperkalemia}$

end

Event *T_Wave_Assessment_Peaked_V12* $\widehat{=}$

extends *T_Wave_Assessment_Peaked_V12*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{T\_Wave\_State(V1)} = \texttt{Peaked} \wedge$
$\texttt{T\_Wave\_State(V2)} = \texttt{Peaked}$

grd3 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd4 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion(l)} < 5000$
step 8 B

grd5 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} := \texttt{normal\_variant}$

end

Event *T_Wave_Assessment_Peaked_V12_MI* $\widehat{=}$
posterior MI using T wave assessment in LEADS V1 and V2

extends *T_Wave_Assessment_Peaked_V12_MI*

when

grd1 : $\texttt{T\_Wave\_State(V1)} = \texttt{Peaked} \wedge$
$\texttt{T\_Wave\_State(V2)} = \texttt{Peaked}$

grd6 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$
grd3 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion}(l) > 5000$
grd4 : $\mathtt{T\_inversion\_l\_d}(\mathtt{V2}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V3}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V4}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V5}) = \mathtt{Localized}$
grd5 : $\mathtt{T\_inversion\_l\_d}(\mathtt{II}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{III}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{aVF}) = \mathtt{Localized}$
grd7 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$
then
act1 : $\mathtt{Disease\_step8} := \mathtt{posterior\_MI}$
end

Event *T_Wave_Assessment_Flat* $\widehat{=}$

extends *T_Wave_Assessment_Flat*

when
grd1 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State}(l) = \mathtt{Flat}$
grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd2 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$
step 8 B
grd3 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion}(l) < 5000$
grd5 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$
then
act1 : $\mathtt{Disease\_step8} := \mathtt{Nonspecific\_ST\_T\_changes}$
act2 : $\mathtt{Disease\_step8\_B} :\in \{\mathtt{Cardiomyopathy}, \mathtt{Electrolyte\_depletion}, \mathtt{Alcohol}, \mathtt{Myocarditis}, \mathtt{Other}\}$
end

Event *T_Wave_Assessment_Inverted_Yes* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_Yes*

when
grd1 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State}(l) = \mathtt{Inverted}$
grd2 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation}(l) = \mathtt{TRUE}$
$\vee$
$\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$
then

act1 : $\texttt{Disease\_step8} :\in \{\texttt{Definite\_ischemia}, \texttt{Probable\_ischemia}, \texttt{Digitalis\_effect}\}$

end

Event *T_Wave_Assessment_Inverted_No* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_No*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Inverted}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation}(\texttt{l}) = \texttt{FALSE}$
$\vee$
$\texttt{Q\_Normal\_Status} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step8} := \texttt{Nonspecific}$

end

Event *T_Wave_Assessment_Inverted_Yes_PM* $\widehat{=}$

PM - pulmonary embolism this disease is already defined in previous development.

extends *T_Wave_Assessment_Inverted_Yes_PM*

when

grd1 : $\texttt{P\_Wave\_Peak}(\texttt{II}) \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak}(\texttt{V1}) \geq 3000$

grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$

grd4 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

$A : step8$ Heart_State = KO

grd7grd5 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$(ST\_elevation(l1) = FALSE \wedge ST\_elevation(k1) = FALSE)$
$\wedge$
$((ST\_seg\_ele(l1) < 1000 \wedge ST\_seg\_ele(k1) < 1000)$
$\vee$
$(Abnormal\_Shaped\_ST(l1) = FALSE \wedge Abnormal\_Shaped\_ST(k1) = FALSE))$
$\Rightarrow l1 \neq k1))$

grd6 : $\texttt{Asy\_T\_Inversion\_strain}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain}(\texttt{V2}) = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain}(\texttt{V3}) = \texttt{TRUE}$

grd8 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step6} := \texttt{pulmonary\_embolism}$

end

Event *T_Wave_Assessment_B* $\widehat{=}$

B for alternate method of T wave assessment

extends *T_Wave_Assessment_B*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{I}, \texttt{II}, \texttt{V3}, \texttt{V4}, \texttt{V5}, \texttt{V6}\} \Rightarrow \texttt{T\_Wave\_State\_B}(\texttt{l}) = \texttt{Upright}$

grd2 : $\texttt{T\_Wave\_State\_B}(\texttt{aVL}) = \texttt{Inverted\_B}$

grd3 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{III}, \texttt{aVL}, \texttt{aVF}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{T\_Wave\_State\_B}(\texttt{l}) = \texttt{Variable}$

then

act1 : $\texttt{T\_Normal\_Status} := \texttt{TRUE}$

end

Event *T_Wave_Assessment_B_DI* $\widehat{=}$

abnormal T wave .....in B ...DI(Definite Ischemia)

extends *T_Wave_Assessment_B_DI*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Inverted}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation}(\texttt{l}) = \texttt{TRUE}$
$\lor$
$\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

grd3 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

added in step-8 B

grd5 : $\texttt{Heart\_State} = \texttt{KO}$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \land \texttt{k} \in \texttt{LEADS} \land$
$((\texttt{ST\_seg\_ele}(\texttt{l}) \geq 1000 \land \texttt{ST\_seg\_ele}(\texttt{k}) \geq 1000) \lor$
$(\texttt{ST\_elevation}(\texttt{l}) = \texttt{TRUE} \land \texttt{ST\_elevation}(\texttt{k}) = \texttt{TRUE})$
$\lor$
$(\texttt{Abnormal\_Shaped\_ST}(\texttt{l}) = \texttt{TRUE} \land \texttt{Abnormal\_Shaped\_ST}(\texttt{k}) = \texttt{TRUE}))$
$\land$
$\texttt{l} \neq \texttt{k}$

added in step-8 B

then

act1 : $\texttt{Disease\_step8} := \texttt{Definite\_ischemia}$

end

Event *T_Inversion_Likely_Ischemia* $\widehat{=}$

probable Ischemia or Likly ischemia

extends *T_Inversion_Likely_Ischemia*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Inverted}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation}(\texttt{l}) = \texttt{TRUE}$
$\lor$
$\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

grd3 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) > 5000$

1 mm= 1000

grd4 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd5 : $\texttt{T\_inversion\_l\_d}(\texttt{V2}) = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d}(\texttt{V3}) = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d}(\texttt{V4}) = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d}(\texttt{V5}) = \texttt{Localized}$

grd6 : $\texttt{T\_inversion\_l\_d}(\texttt{II}) = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d}(\texttt{III}) = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d}(\texttt{aVF}) = \texttt{Localized}$

b. of Deep inversion ¿ 5mm

grd7 : $\texttt{Heart\_State} = \texttt{KO}$
grd8 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step8} := \texttt{Probable\_ischemia}$

end

Event *T_Inversion_Diffuse_B* $\widehat{=}$

Step 8 B for c.

extends *T_Inversion_Diffuse_B*

when

grd1 : $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) > \texttt{5000}$
grd3 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion\_l\_d}(\texttt{l}) = \texttt{Diffuse}$
grd4 : $\texttt{Heart\_State} = \texttt{KO}$
grd5 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step8\_B} :\in \{\texttt{Cardiomyopathy}, \texttt{other\_nonspecific}\}$

end

Event *Axis_Assessment_QRS_upright_Yes* $\widehat{=}$

when

grd1 : $QRS\_Axis\_State(I) = D\_Upright \wedge$
$QRS\_Axis\_State(aVF) = D\_Upright$

then

act1 : $minAngle :\in \{0, -30\}$
act2 : $maxAngle :\in \{110, 90\}$

end

Event *Axis_Assessment_QRS_upright_No* $\widehat{=}$

when

grd1 : $(QRS\_Axis\_State(I) \neq D\_Upright \vee$
$QRS\_Axis\_State(aVF) \neq D\_Upright)$

then

act1 : $minAngle :\in \{-30, 110\}$
act2 : $maxAngle :\in \{-90, 180\}$

end

END

An Event-B Specification of Step9_Axis_Assessment_Ref1
Generated Date: 25 Nov 2010 @ 03:39:44 PM

MACHINE Step9_Axis_Assessment_Ref1

REFINES Step9_Axis_Assessment

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

`ST_seg_ele` ST segment for elevation 1mm=0.1mV

`Disease_step4`

`Q_Width` Q wave width

`Q_Depth` Q wave depth

`Q_Normal_Status` Q wave normal or abnormal

`Age_of_Inf` Age of Infarct

`Disease_step5`

`Mice_State`

`R_Depth` R wave depth or height (also use in Step 7)

`R_Normal_Status` R wave normal or abnormal

`Q_Wave_State` Q wave states for all LEADS

`P_Wave_Peak` function to estimate the peak of LEADS signal

`Disease_step6`

`PP_Interval`

`RR_Interval`

`Diphasic`

`P_Wave_Broad`

`S_Depth` S wave depth or height

`R_S_Ratio` R wave and S wave Ratio function

`T_Wave_State` T wave patterns...

`Disease_step8`

`T_Wave_State_B` B for alternative method of T wave assessment

`T_Normal_Status` T wave normal or abnormal

`Abnormal_Shaped_ST`

`Asy_T_Inversion_strain` Asymmetric T wave Inversion strain pattern

`T_inversion` Deep T wave inversion

`T_inversion_l_d` T inversion Localized and Diffuse

`Disease_step8_B`

`QRS_Axis_State` QRS Axis Direction

`minAngle` min. value of angle of Axis in degree

`maxAngle` max. value of angle of Axis in degree

`Axis_Devi` Axis Deviation in LEADS...

`Disease_step9`

`ST_depression`

INVARIANTS

inv1 : $Axis\_Devi \in Axis\_deviation$

inv2 : $Disease\_step9 \in Disease\_Codes\_Step9$

inv3 : $Disease\_step9 \in \{LPFB, Dextrocardia, NV\_MSEC\} \land maxAngle = 180 \land minAngle = 110 \Rightarrow Heart\_State = KO$

inv4 : $Disease\_step9 \in \{LAFB, MSCHD, Some\_Form\_VT, ED\_OC\} \land maxAngle = -90 \land minAngle = -30 \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : `RR_Int_equidistant` $:\in$ LEADS $\rightarrow$ BOOL

act2 : `PP_Int_equidistant` $:\in$ LEADS $\rightarrow$ BOOL

act3 : `P_Positive` $:\in$ LEADS $\rightarrow$ BOOL

act4 : `Sinus` $:=$ No

act5 : `PP_Interval` $:\in$ LEADS $\rightarrow \mathbb{N}$

act6 : `RR_Interval` $:\in$ LEADS $\rightarrow \mathbb{N}$

act7 : `Heart_Rate` $:\in 1 .. 300$

act8 : `Heart_State` $:=$ KO

act9 : `PR_Int` $:= 120$

act10 : `Disease_step2` $:=$ NDS2

act11 : `QRS_Int` $:= 50$

act12 : `Notched_R` $:\in$ LEADS $\rightarrow$ BOOL

act13 : `Small_R_QS` $:\in$ LEADS $\rightarrow$ BOOL

act14 : `Slurred_S_duration` $:\in$ LEADS $\rightarrow \mathbb{N}_1$

act15 : `M_Shape_Complex` $:\in$ LEADS $\rightarrow$ BOOL

act16 : `Slurred_S` $:\in$ LEADS $\rightarrow$ BOOL

act17 : `ST_elevation` $:\in$ LEADS $\rightarrow$ BOOL

act18 : `Epsilon_Wave` $:\in$ LEADS $\rightarrow$ BOOL

act19 : $\texttt{Delta\_Wave} := 0$
act20 : $\texttt{Disease\_step3} := \texttt{NDS3}$
act21 : $\texttt{ST\_seg\_ele} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act22 : $\texttt{Disease\_step4} := \texttt{NDS4}$
act57 : $\texttt{ST\_depression} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act23 : $\texttt{Q\_Width} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act24 : $\texttt{Q\_Depth} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act25 : $\texttt{Q\_Normal\_Status} := \texttt{FALSE}$
act26 : $\texttt{Mice\_State} := \texttt{NMS}$
act27 : $\texttt{R\_Depth} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act28 : $\texttt{R\_Normal\_Status} := \texttt{FALSE}$
act29 : $\texttt{Q\_Wave\_State} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$
act30 : $\texttt{Age\_of\_Inf} :\in \texttt{Age\_of\_Infarct}$
act31 : $\texttt{Disease\_step5} := \texttt{NDS5}$
act32 : $\texttt{Diphasic} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$
act33 : $\texttt{P\_Wave\_Broad} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act34 : $\texttt{P\_Wave\_Peak} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act35 : $\texttt{Disease\_step6} := \texttt{NDS6}$
act36 : $\texttt{S\_Depth} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act37 : $\texttt{R\_S\_Ratio} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act38 : $\texttt{T\_Wave\_State} :\in \texttt{LEADS} \rightarrow \texttt{T\_State}$
act39 : $\texttt{Disease\_step8} := \texttt{NDS8}$
act40 : $\texttt{Abnormal\_Shaped\_ST} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$
act41 : $\texttt{Asy\_T\_Inversion\_strain} :\in \texttt{LEADS} \rightarrow \texttt{BOOL}$
act43 : $\texttt{T\_inversion\_l\_d} :\in \texttt{LEADS} \rightarrow \texttt{T\_State\_l\_d}$
act42 : $\texttt{T\_inversion} :\in \texttt{LEADS} \rightarrow \mathbb{N}$
act44 : $\texttt{Disease\_step8\_B} := \texttt{NDS8B}$
act45 : $\texttt{T\_Wave\_State\_B} :\in \texttt{LEADS} \rightarrow \texttt{T\_State\_B}$
act46 : $\texttt{T\_Normal\_Status} := \texttt{FALSE}$
act47 : $\texttt{QRS\_Axis\_State} :\in \texttt{LEADS} \rightarrow \texttt{QRS\_directions}$
act48 : $\texttt{minAngle} := 0$
act49 : $\texttt{maxAngle} := 0$
act50 : $Axis\_Devi := ND$
act51 : $Disease\_step9 := NDS9$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any
rate

where
grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l}))$
$\land$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$
grd4 : $\texttt{rate} \in 60 \,..\, 100$
60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$

Heart is Normal if PR ≤ 200 QRS_Int < 120

$HeartisNormalifQRS < 120$

grdgrd7 : $Disease\_step2 = NDS2$

grd8 : $Disease\_step3 = NDS3$

grd9 : $Disease\_step4 = NDS4$

grd10 : $Disease\_step5 = NDS5$

grd11 : $Disease\_step6 = NDS6$

grd12 : $Disease\_step8 = NDS8$

grd13 : $Disease\_step8\_B = NDS8B$

grd14 : $Disease\_step9 = NDS9$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$

Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor RR\_Int\_equidistant(l) = FALSE \lor RR\_Interval(l) \neq PP\_Interval(l)) \lor P\_Positive(II) = FALSE$

grd2 : $rate \in 1 .. 300$

then

act1 : $Sinus := No$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land RR\_Int\_equidistant(l) = TRUE \land RR\_Interval(l) = PP\_Interval(l)) \land P\_Positive(II) = TRUE$

grd5 : $rate \in 1 .. 300 \setminus 60 .. 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $Disease\_step3 = WPW\_Syndrome \lor Disease\_step3 = Brugada\_Syndrome \lor Disease\_step3 = RV\_Dysplasia \lor Disease\_step3 = IVCD$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\texttt{pr} \in 120 \,..\, 220$

time interval in (ms.)

grd2 : $\texttt{pr} > 200$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{PR\_Int} := \texttt{pr}$

act2 : $\texttt{Disease\_step2} := \texttt{First\_degree\_AV\_Block}$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{Notched\_R}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Notched\_R}(\texttt{V6}) = \texttt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\texttt{Small\_R\_QS}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Small\_R\_QS}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$

from step 5

grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

from step 5

grd9 : $Axis\_Devi = LAD \wedge$
$minAngle = -30 \wedge$
$maxAngle = -90$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$

Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{M\_Shape\_Complex}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S}(\texttt{I}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{TRUE}$

grd8 : $\texttt{Slurred\_S\_duration}(\texttt{I}) > 40 \wedge$
$\texttt{Slurred\_S\_duration}(\texttt{V5}) > 40 \wedge$
$\texttt{Slurred\_S\_duration}(\texttt{V6}) > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$

QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt

d_wave

exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \vee \texttt{sympt} = \texttt{A\_LBBB}$

grd3 : $\texttt{d\_wave} \in \mathbb{N}$

grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$
Delta Wave + PR $\leq$ 120 `Heart_State = KO`

grd5grd6 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd7 : $\texttt{exmi} \in \texttt{Mice\_State5} \wedge \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act2 : $\texttt{Delta\_Wave} := \texttt{d\_wave}$

act3 : $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$
grd2 : $\texttt{Heart\_State} = \texttt{KO}$
grd3 : $\texttt{QRS\_Int} \geq 110$
grd4 : $\texttt{Slurred\_S}(\texttt{V5}) = \texttt{FALSE} \land$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{FALSE}$
grd5 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$
grd6 : $\texttt{ST\_elevation}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{ST\_elevation}(\texttt{V2}) = \texttt{TRUE}$
grd7 : $\texttt{Sinus} = \texttt{Yes}$

then

act1 : $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$
grd2 : $\texttt{Heart\_State} = \texttt{KO}$
grd3 : $\texttt{QRS\_Int} \geq 110$
grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$
grd5 : $\texttt{Epsilon\_Wave}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{Epsilon\_Wave}(\texttt{V3}) = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$
grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$
grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event $ST\_seg\_elevation\_YES \widehat{=}$
ST segment elevation...

extends $ST\_seg\_elevation\_YES$

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\mathtt{Disease\_step4} \in \{\mathtt{Acute\_inferior\_MI}, \mathtt{Acute\_anterior\_MI}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{STEMI}$

end

Event $ST\_seg\_elevation\_NOTCKMB\_Yes \widehat{=}$
Troponin or CK-MB positive YES

extends $ST\_seg\_elevation\_NOTCKMB\_Yes$

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression(l)} \geq 1000 \wedge \mathtt{ST\_depression(k)} \geq 1000)$
$\wedge\, \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \in \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Non\_STEMI}$

end

Event $ST\_seg\_elevation\_NO\_TCKMB\_No \widehat{=}$
Troponin or CK-MB positive No

extends $ST\_seg\_elevation\_NO\_TCKMB\_No$

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression}(\mathtt{l}) \geq 1000 \wedge \mathtt{ST\_depression}(\mathtt{k}) \geq 1000)$
$\wedge \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \notin \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

grd6 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion}(\mathtt{l}) < 5000$

grd7 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : $\mathtt{Q\_Width}(\mathtt{II}) < 40 \wedge \mathtt{Q\_Depth}(\mathtt{II}) \leq 3000 \wedge$
$\mathtt{Q\_Width}(\mathtt{aVF}) < 40 \wedge \mathtt{Q\_Depth}(\mathtt{aVF}) \leq 3000 \wedge$
$\mathtt{Q\_Width}(\mathtt{aVL}) < 40$

1000 micrometer= 1 milimeter

grd2 : $\mathtt{Q\_Width}(\mathtt{III}) \leq 40 \wedge \mathtt{Q\_Depth}(\mathtt{III}) \leq 7000 \wedge \mathtt{Q\_Depth}(\mathtt{aVL}) \leq 7000$

grd3 : $\mathtt{Q\_Depth}(\mathtt{I}) < 40 \wedge \mathtt{Q\_Depth}(\mathtt{I}) \leq 1500$

then

act1 : $\mathtt{Q\_Normal\_Status} := \mathtt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\mathtt{Q\_Width}(\mathtt{V5}) \geq 40 \wedge \mathtt{Q\_Depth}(\mathtt{V5}) > 3000 \wedge$
$\mathtt{Q\_Width}(\mathtt{V6}) \geq 40 \wedge \mathtt{Q\_Depth}(\mathtt{V6}) > 3000$

grd5 : $\mathtt{Q\_Width}(\mathtt{aVL}) \geq 40 \wedge \mathtt{Q\_Depth}(\mathtt{aVL}) > 7000$

$grd6:$ $\mathtt{Q\_Depth(I)} \geq 40 \wedge \mathtt{Q\_Depth(I)} > 1500$
$grd7:$ $\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Acute\_anterior\_MI}$

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$

$$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$$
$$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$$
$$\wedge$$
$$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$$
$$\wedge\, l1 \neq k1$$
$$\wedge$$
$$($$
$$(l1 = V1 \wedge k1 = V2) \vee$$
$$(l1 = V2 \wedge k1 = V3) \vee$$
$$(l1 = V3 \wedge k1 = V4) \vee$$
$$(l1 = V4 \wedge k1 = V5) \vee$$
$$(l1 = V5 \wedge k1 = V6)$$
$$)$$
$$))$$

grd4 : $\mathtt{Q\_Width(II)} \geq 40 \wedge \mathtt{Q\_Depth(II)} > 3000 \wedge$
$\mathtt{Q\_Width(III)} > 40 \wedge \mathtt{Q\_Depth(III)} > 7000 \wedge$
$\mathtt{Q\_Width(aVF)} \geq 40 \wedge \mathtt{Q\_Depth(aVF)} > 3000$

grd5 : $\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Acute\_inferior\_MI}$

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\mathtt{Disease\_step4} = \mathtt{Acute\_inferior\_MI}$
$\vee$
$\mathtt{Disease\_step5} \in \{\mathtt{anterior\_MI}, \mathtt{LVH}, \mathtt{emphysema}\}$
$\vee$
$\mathtt{Mice\_State} = \mathtt{Exclude\_Mimics\_MI}$
$\vee$
$\mathtt{Disease\_step2} = \mathtt{LBBB}$

then

act1 : $\mathtt{Age\_of\_Inf} :\in \{\mathtt{recent}, \mathtt{old}, \mathtt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\mathtt{Disease\_step4} = \mathtt{Acute\_inferior\_MI}$

grd2 : $\mathtt{exmi} \in \mathtt{Mice\_State5} \land \mathtt{exmi} = \mathtt{Exclude\_Mimics\_MI}$

then

act1 : $\mathtt{Disease\_step5} := \mathtt{Hypertrophic\_cardiomyopathy}$

act2 : $\mathtt{Mice\_State} := \mathtt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\mathtt{R\_Depth}(\mathtt{V1}) \geq 0 \land \mathtt{R\_Depth}(\mathtt{V1}) \leq 6000 \land \mathtt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\mathtt{R\_Depth}(\mathtt{V2}) > 200 \land \mathtt{R\_Depth}(\mathtt{V2}) \leq 12000$

grd3 : $\mathtt{R\_Depth}(\mathtt{V2}) \geq 1000 \land \mathtt{R\_Depth}(\mathtt{V2}) \leq 24000$

then

act1 : $\mathtt{R\_Normal\_Status} := \mathtt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Mice\_State} :\in \{\mathtt{late\_transition}, \mathtt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$

grd2 : $\mathtt{Q\_Wave\_State}(\mathtt{V1}) = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State}(\mathtt{V2}) = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State}(\mathtt{V3}) = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State}(\mathtt{V4}) = \mathtt{TRUE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} :\in \{\mathtt{anterior\_MI}, \mathtt{LVH}, \mathtt{emphysema}\}$

act2 : $\mathtt{Mice\_State} := \mathtt{Exclude\_Mimics\_MI}$

end

Event $R\_Q\_Assessment\_R\_Abnormal\_V56 \;\widehat{=}$
R wave abnormal , pathologic Q waves consider in V5-V6

refines $R\_Q\_Assessment\_R\_Abnormal\_V56$

when

grd1 : $Q\_Wave\_State(V5) = TRUE \wedge$
$Q\_Wave\_State(V6) = TRUE$

grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step5 := Hypertrophic\_cardiomyopathy$

end

Event $P\_Wave\_assessment\_Peaked\_Broad\_No \;\widehat{=}$

extends $P\_Wave\_assessment\_Peaked\_Broad\_No$

when

grd1 : $(\mathtt{P\_Wave\_Peak}(\mathtt{II}) < 3000 \wedge$
$\mathtt{P\_Wave\_Peak}(\mathtt{V1}) < 3000)$
$\vee$
$(\mathtt{P\_Wave\_Broad}(\mathtt{II}) < 110 \wedge \mathtt{P\_Wave\_Broad}(\mathtt{V1}) < 110) \vee$
$\mathtt{Diphasic}(\mathtt{II}) = \mathtt{FALSE} \vee$
$\mathtt{Diphasic}(\mathtt{V1}) = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{NDS6}$

end

Event $P\_Wave\_assessment\_Peaked\_Yes \;\widehat{=}$

extends $P\_Wave\_assessment\_Peaked\_Yes$

when

grd1 : $\mathtt{P\_Wave\_Peak}(\mathtt{II}) \geq 3000$

grd2 : $\mathtt{P\_Wave\_Peak}(\mathtt{V1}) \geq 3000$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RAE}$

end

Event $P\_Wave\_assessment\_Peaked\_Yes\_Check\_RAE \;\widehat{=}$

extends $P\_Wave\_assessment\_Peaked\_Yes\_Check\_RAE$

when

grd1 : $\mathtt{P\_Wave\_Peak}(\mathtt{II}) \geq 3000$

grd2 : $\mathtt{P\_Wave\_Peak}(\mathtt{V1}) \geq 3000$

grd3 : $\mathtt{Disease\_step6} = \mathtt{RAE}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RV\_strain}$

end

Event $P\_Wave\_assessment\_Broad\_Yes \;\widehat{=}$

extends $P\_Wave\_assessment\_Broad\_Yes$

when

$\text{grd1}: (\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \land \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \lor$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \lor$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$

$\text{grd2}: \texttt{Heart\_State} = \texttt{KO}$

then

$\text{act1}: \texttt{Disease\_step6} := \texttt{LAE}$

end

Event *P_Wave_assessment_Broad_Yes_Check_LAE* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes_Check_LAE*

when

$\text{grd1}: (\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \land \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \lor$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \lor$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$

$\text{grd2}: \texttt{Disease\_step6} = \texttt{LAE}$

$\text{grd3}: \texttt{Heart\_State} = \texttt{KO}$

then

$\text{act1}: \texttt{Disease\_step6} :\in \{\texttt{mitral\_stenosis}, \texttt{mitral\_regurgitation},$
$\texttt{LV\_failure}, \texttt{dilated\_cardiomyopathy}\}$

end

Event *LVH_Assessment* $\widehat{=}$

LVH Assessment

extends *LVH_Assessment*

any

`LVH_specificity` specificity in percentage

`sensitivity` sensitivity in percentage

`sex`

where

$\text{grd1}: (\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \land \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \lor$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \lor$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$

$\text{grd2}: \texttt{Disease\_step6} = \texttt{LAE}$

$\text{grd5}: \texttt{sex} \in \{0, 1\}$

o for men and 1 for women

$\text{grd3}: ((\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V5})) > 35000$
$\lor$
$(\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V6})) > 35000)$

1mm = 1000 micrometer............. 1 assessment

$\text{grd4}: ((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 24000) \land \texttt{sex} = 0)$
$\lor$
$((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 18000) \land \texttt{sex} = 1)$

2 assessment

$\text{grd6}: \texttt{LVH\_specificity} = 90$
$\land$
$\texttt{sensitivity} < 40$

1 and 2 assessment

$\text{grd7}: \texttt{Disease\_step6} = \texttt{LAE} \Rightarrow \texttt{LVH\_specificity} < 98$

3 assesssment

grd8 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$
A or B : from step 8 development

grd9 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd10 : $\texttt{Asy\_T\_Inversion\_strain(V5)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V6)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V4)} = \texttt{TRUE}$

grd11 : $\texttt{Heart\_State} = \texttt{KO}$

grd12 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

grd13 : $Axis\_Devi = LAD \wedge$
$minAngle = -30 \wedge$
$maxAngle = -90$

then

act1 : $\texttt{Disease\_step6} := \texttt{LVH\_cause}$

end

Event $RVH\_Assessment \widehat{=}$
RVH Assessment

extends $RVH\_Assessment$

any

age age od men or women
aixs axis for deviation

where

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$

grd4 : $\texttt{R\_Depth(V1)} \geq 7000 \wedge \texttt{age} > 30$
1 assessment

grd5 : $\texttt{S\_Depth(V5)} \geq 7000 \vee$
$\texttt{S\_Depth(V6)} \geq 7000$
2 assessment

grd6 : $\texttt{R\_S\_Ratio(V1)} \geq 100$
R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment

grd7 : $\texttt{R\_S\_Ratio(V5)} \leq 100$
$\vee$
$\texttt{R\_S\_Ratio(V6)} \leq 100$
4 assessment

grd8 : $\texttt{aixs} \in 0\,..\,360 \wedge \texttt{aixs} \geq 110$
5 assessment

grd9 : $\texttt{Disease\_step2} \notin \{\texttt{LBBB}, \texttt{RBBB}\}$

grd10 : $\texttt{QRS\_Int} < 120$

grd11 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

$AorB : fromstep8development$

$\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$

$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$

$\vee$

$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$

$\wedge$

$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$

$\Rightarrow l1 \neq k1))$

grd12grd13 : $\mathtt{Asy\_T\_Inversion\_strain(V1)} = \mathtt{TRUE} \wedge$
$\mathtt{Asy\_T\_Inversion\_strain(V2)} = \mathtt{TRUE} \wedge$
$\mathtt{Asy\_T\_Inversion\_strain(V3)} = \mathtt{TRUE}$

grd14 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd15 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

grd16 : $Axis\_Devi = RAD \wedge$
$minAngle = 110 \wedge$
$maxAngle = 180$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RVH}$

end

Event $T\_Wave\_Assessment\_Peaked\_V123456$ $\widehat{=}$

T Wave Assessment

extends $T\_Wave\_Assessment\_Peaked\_V123456$

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{V1}, \mathtt{V2}, \mathtt{V3}, \mathtt{V4}, \mathtt{V5}, \mathtt{V6}\} \Rightarrow \mathtt{T\_Wave\_State(l)} = \mathtt{Peaked}$

then

act1 : $\mathtt{Disease\_step8} := \mathtt{Hyperkalemia}$

end

Event $T\_Wave\_Assessment\_Peaked\_V12$ $\widehat{=}$

extends $T\_Wave\_Assessment\_Peaked\_V12$

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$

grd2 : $\mathtt{T\_Wave\_State(V1)} = \mathtt{Peaked} \wedge$
$\mathtt{T\_Wave\_State(V2)} = \mathtt{Peaked}$

grd3 : $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$

$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$

$\vee$

$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$

$\wedge$

$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$

$\Rightarrow l1 \neq k1))$

grd4 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion(l)} < 5000$

step 8 B

grd5 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

grd6 : $\vee$

$(\mathrm{Axis\_Devi} = \mathrm{RAD} \wedge$
$minAngle = 110 \wedge$
$maxAngle = 180)$

then

act1 : Mice_State := normal_variant

end

Event *T_Wave_Assessment_Peaked_V12_MI* $\widehat{=}$

posterior MI using T wave assessment in LEADS V1 and V2

extends *T_Wave_Assessment_Peaked_V12_MI*

when

grd1 : T_Wave_State(V1) = Peaked ∧
T_Wave_State(V2) = Peaked

grd6 : Heart_State = KO

grd2 : ∨

$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd3 : ∀l·l ∈ LEADS ⇒ T_inversion(l) > 5000

grd4 : T_inversion_l_d(V2) = Localized ∧
T_inversion_l_d(V3) = Localized ∧
T_inversion_l_d(V4) = Localized ∧
T_inversion_l_d(V5) = Localized

grd5 : T_inversion_l_d(II) = Localized ∧
T_inversion_l_d(III) = Localized ∧
T_inversion_l_d(aVF) = Localized

grd7 : T_Normal_Status = FALSE

then

act1 : Disease_step8 := posterior_MI

end

Event *T_Wave_Assessment_Flat* $\widehat{=}$

extends *T_Wave_Assessment_Flat*

when

grd1 : ∀l·l ∈ LEADS ⇒ T_Wave_State(l) = Flat

grd4 : Heart_State = KO

grd2 : ∨

$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

step 8 B

grd3 : ∀l·l ∈ LEADS ⇒ T_inversion(l) < 5000

grd5 : T_Normal_Status = FALSE

then

act1 : Disease_step8 := Nonspecific_ST_T_changes

act2 : Disease_step8_B :∈ {Cardiomyopathy, Electrolyte_depletion, Alcohol, Myocarditis, Other}

end

Event *T_Wave_Assessment_Inverted_Yes* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_Yes*

when

grd1 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State}(l) = \mathtt{Inverted}$

grd2 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation}(l) = \mathtt{TRUE}$
$\lor$
$\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step8} :\in \{\mathtt{Definite\_ischemia}, \mathtt{Probable\_ischemia}, \mathtt{Digitalis\_effect}\}$

end

Event *T_Wave_Assessment_Inverted_No* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_No*

when

grd1 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State}(l) = \mathtt{Inverted}$

grd2 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation}(l) = \mathtt{FALSE}$
$\lor$
$\mathtt{Q\_Normal\_Status} = \mathtt{TRUE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step8} := \mathtt{Nonspecific}$

end

Event *T_Wave_Assessment_Inverted_Yes_PM* $\widehat{=}$

PM - pulmonary embolism this disease is already defined in previous development.

extends *T_Wave_Assessment_Inverted_Yes_PM*

when

grd1 : $\mathtt{P\_Wave\_Peak}(\mathtt{II}) \geq 3000$

grd2 : $\mathtt{P\_Wave\_Peak}(\mathtt{V1}) \geq 3000$

grd3 : $\mathtt{Disease\_step6} = \mathtt{RAE}$

grd4 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

$A : step8$ `Heart_State = KO`

grd17grd5 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$(ST\_elevation(l1) = FALSE \land ST\_elevation(k1) = FALSE)$
$\land$
$((ST\_seg\_ele(l1) < 1000 \land ST\_seg\_ele(k1) < 1000)$
$\lor$
$(Abnormal\_Shaped\_ST(l1) = FALSE \land Abnormal\_Shaped\_ST(k1) = FALSE))$
$\Rightarrow l1 \neq k1))$

grd6 : $\mathtt{Asy\_T\_Inversion\_strain}(\mathtt{V1}) = \mathtt{TRUE} \land$
$\mathtt{Asy\_T\_Inversion\_strain}(\mathtt{V2}) = \mathtt{TRUE} \land$
$\mathtt{Asy\_T\_Inversion\_strain}(\mathtt{V3}) = \mathtt{TRUE}$

grd8 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

grd9 : $Axis\_Devi = RAD \land$
$minAngle = 110 \land$
$maxAngle = 180$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{pulmonary\_embolism}$

end

Event $T\_Wave\_Assessment\_B \mathrel{\widehat{=}}$
B for alternate method of T wave assessment

extends $T\_Wave\_Assessment\_B$

when

grd1 : $\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{I}, \mathtt{II}, \mathtt{V3}, \mathtt{V4}, \mathtt{V5}, \mathtt{V6}\} \Rightarrow \mathtt{T\_Wave\_State\_B}(\mathtt{l}) = \mathtt{Upright}$

grd2 : $\mathtt{T\_Wave\_State\_B}(\mathtt{aVL}) = \mathtt{Inverted\_B}$

grd3 : $\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{III}, \mathtt{aVL}, \mathtt{aVF}, \mathtt{V1}, \mathtt{V2}\} \Rightarrow \mathtt{T\_Wave\_State\_B}(\mathtt{l}) = \mathtt{Variable}$

then

act1 : $\mathtt{T\_Normal\_Status} := \mathtt{TRUE}$

end

Event $T\_Wave\_Assessment\_B\_DI \mathrel{\widehat{=}}$
abnormal T wave .....in B ...DI(Definite Ischemia)

extends $T\_Wave\_Assessment\_B\_DI$

when

grd1 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State}(\mathtt{l}) = \mathtt{Inverted}$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation}(\mathtt{l}) = \mathtt{TRUE}$
$\lor$
$\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

grd3 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$
added in step-8 B

grd5 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \land \mathtt{k} \in \mathtt{LEADS} \land$
$((\mathtt{ST\_seg\_ele}(\mathtt{l}) \geq 1000 \land \mathtt{ST\_seg\_ele}(\mathtt{k}) \geq 1000) \lor$
$(\mathtt{ST\_elevation}(\mathtt{l}) = \mathtt{TRUE} \land \mathtt{ST\_elevation}(\mathtt{k}) = \mathtt{TRUE})$
$\lor$
$(\mathtt{Abnormal\_Shaped\_ST}(\mathtt{l}) = \mathtt{TRUE} \land \mathtt{Abnormal\_Shaped\_ST}(\mathtt{k}) = \mathtt{TRUE}))$
$\land$
$\mathtt{l} \neq \mathtt{k}$
added in step-8 B

then

act1 : $\mathtt{Disease\_step8} := \mathtt{Definite\_ischemia}$

end

Event $T\_Inversion\_Likely\_Ischemia \mathrel{\widehat{=}}$
probable Ischemia or Likly ischemia

extends $T\_Inversion\_Likely\_Ischemia$

when

grd1 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State}(\mathtt{l}) = \mathtt{Inverted}$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation}(\mathtt{l}) = \mathtt{TRUE}$
$\lor$
$\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

grd3 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion}(l) > 5000$

1 mm= 1000

grd4 : $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd5 : $\mathtt{T\_inversion\_l\_d}(\mathtt{V2}) = \mathtt{Localized} \wedge$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V3}) = \mathtt{Localized} \wedge$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V4}) = \mathtt{Localized} \wedge$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V5}) = \mathtt{Localized}$

grd6 : $\mathtt{T\_inversion\_l\_d}(\mathtt{II}) = \mathtt{Localized} \wedge$
$\mathtt{T\_inversion\_l\_d}(\mathtt{III}) = \mathtt{Localized} \wedge$
$\mathtt{T\_inversion\_l\_d}(\mathtt{aVF}) = \mathtt{Localized}$

b. of Deep inversion ¿ 5mm

grd7 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd8 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step8} := \mathtt{Probable\_ischemia}$

end

Event *T_Inversion_Diffuse_B* $\widehat{=}$

Step 8 B for c.

extends *T_Inversion_Diffuse_B*

when

grd1 : $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd2 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion}(l) > 5000$

grd3 : $\forall l \cdot l \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion\_l\_d}(l) = \mathtt{Diffuse}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd5 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step8\_B} :\in \{\mathtt{Cardiomyopathy}, \mathtt{other\_nonspecific}\}$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_less_40* $\widehat{=}$

refines *Axis_Assessment_QRS_upright_Yes*

any

age

where

grd1 : $QRS\_Axis\_State(I) = D\_Upright \wedge$
$QRS\_Axis\_State(aVF) = D\_Upright$

grd2 : $age \in \mathbb{N} \land age < 40$

then

act1 : $minAngle := 0$

act2 : $maxAngle := 110$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_gre_40* $\widehat{=}$

refines *Axis_Assessment_QRS_upright_Yes*

any

age

where

grd1 : $QRS\_Axis\_State(I) = D\_Upright \land QRS\_Axis\_State(aVF) = D\_Upright$

grd2 : $age \in \mathbb{N} \land age > 40$

then

act1 : $minAngle := -30$

act2 : $maxAngle := 90$

end

Event *Axis_Assessment_QRS_upright_No_QRS_positive* $\widehat{=}$

refines *Axis_Assessment_QRS_upright_No*

when

grd1 : $\neg(QRS\_Axis\_State(I) = D\_Upright \land QRS\_Axis\_State(aVF) = D\_Upright)$

grd2 : $QRS\_Axis\_State(I) = D\_Positive \land QRS\_Axis\_State(aVF) = D\_Positive$

grd3 : $Heart\_State = KO$

then

act1 : $minAngle := -30$

act2 : $maxAngle := -90$

act3 : $Axis\_Devi := LAD$

end

Event *Axis_Assessment_QRS_upright_No_QRS_negative* $\widehat{=}$

refines *Axis_Assessment_QRS_upright_No*

when

grd1 : $\neg(QRS\_Axis\_State(I) = D\_Upright \land QRS\_Axis\_State(aVF) = D\_Upright)$

grd2 : $QRS\_Axis\_State(I) = D\_Negative \land QRS\_Axis\_State(aVF) = D\_Negative$

grd3 : $Heart\_State = KO$

then

act1 : $minAngle := 110$

act2 : $maxAngle := 180$

act3 : $Axis\_Devi := RAD$

end

Event *Misc_Disease_Step9_LAD* $\widehat{=}$

when

grd1 : $Axis\_Devi = LAD \wedge$
$minAngle = -30 \wedge$
$maxAngle = -90$

grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step9 :\in \{LAFB, MSCHD, Some\_Form\_VT, ED\_OC\}$

end

Event $Misc\_Disease\_Step9\_RAD \;\widehat{=}$

when

grd1 : $Axis\_Devi = RAD \wedge$
$minAngle = 110 \wedge$
$maxAngle = 180$

grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step9 :\in \{LPFB, Dextrocardia, NV\_MSEC\}$

end

Event $R\_Q\_Assessment\_R\_Abnormal\_V56\_axis\_deviation \;\widehat{=}$

refines $R\_Q\_Assessment\_R\_Abnormal\_V56$

when

grd1 : $Q\_Wave\_State(V5) = TRUE \wedge$
$Q\_Wave\_State(V6) = TRUE$

grd2 : $Axis\_Devi = RAD \wedge$
$minAngle = 110 \wedge$
$maxAngle = 180$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step5 := lateral\_MI$

end

END

An Event-B Specification of Step10_ctx
Generated Date: 25 Nov 2010 @ 03:38:51 PM

CONTEXT Step10_ctx

SETS

Misc_Disease_Codes_Step10

CONSTANTS

Incomplete_RBBB Atrial Septal Defect

Pericarditis

Long_QT

Hypokalemia

Digitalis_toxicity

Electrical_alternans

Electronic_pacing

Hypothermia

Hypercalcemia

NDS10

AXIOMS

axm1 : $Misc\_Disease\_Codes\_Step10 = \{Incomplete\_RBBB, Pericarditis, Long\_QT, Hypokalemia, Digitalis\_toxicity, Electrical\_alternans, Electronic\_pacing, Hypothermia, Hypercalcemia, NDS10\}$

axm2 : $\neg Incomplete\_RBBB = Pericarditis$

axm3 : $\neg Incomplete\_RBBB = Long\_QT$

axm4 : $\neg Incomplete\_RBBB = Hypokalemia$

axm6 : $\neg Incomplete\_RBBB = Digitalis\_toxicity$

axm7 : $\neg Incomplete\_RBBB = Electrical\_alternans$

axm8 : $\neg Incomplete\_RBBB = Electronic\_pacing$

axm9 : $\neg Incomplete\_RBBB = Hypothermia$

axm10 : $\neg Incomplete\_RBBB = Hypercalcemia$

axm11 : $\neg Incomplete\_RBBB = NDS10$

axm12 : $\neg Pericarditis = Long\_QT$

axm13 : $\neg Pericarditis = Hypokalemia$

axm15 : $\neg Pericarditis = Digitalis\_toxicity$

axm16 : $\neg Pericarditis = Electrical\_alternans$

axm17 : $\neg Pericarditis = Electronic\_pacing$

axm18 : $\neg Pericarditis = Hypothermia$

axm19 : $\neg Pericarditis = Hypercalcemia$

axm20 : $\neg Pericarditis = NDS10$

axm21 : $\neg Long\_QT = Hypokalemia$

axm23 : $\neg Long\_QT = Digitalis\_toxicity$

axm24 : $\neg Long\_QT = Electrical\_alternans$

axm25 : $\neg Long\_QT = Electronic\_pacing$

axm26 : $\neg Long\_QT = Hypothermia$

axm27 : $\neg Long\_QT = Hypercalcemia$

axm28 : $\neg Long\_QT = NDS10$

axm30 : $\neg Hypokalemia = Digitalis\_toxicity$

axm31 : $\neg Hypokalemia = Electrical\_alternans$

axm32 : $\neg Hypokalemia = Electronic\_pacing$

axm33 : $\neg Hypokalemia = Hypothermia$

axm34 : $\neg Hypokalemia = Hypercalcemia$

axm35 : $\neg Hypokalemia = NDS10$

axm42 : $\neg Digitalis\_toxicity = Electrical\_alternans$

axm43 : $\neg Digitalis\_toxicity = Electronic\_pacing$

axm44 : $\neg Digitalis\_toxicity = Hypothermia$

axm45 : $\neg Digitalis\_toxicity = Hypercalcemia$

axm46 : $\neg Digitalis\_toxicity = NDS10$

axm47 : $\neg Electrical\_alternans = Electronic\_pacing$

axm48 : $\neg Electrical\_alternans = Hypothermia$

axm49 : $\neg Electrical\_alternans = Hypercalcemia$

axm50 : $\neg Electrical\_alternans = NDS10$

axm51 : $\neg Electronic\_pacing = Hypothermia$

axm52 : $\neg Electronic\_pacing = Hypercalcemia$

axm53 : $\neg Electronic\_pacing = NDS10$

axm54 : $\neg Hypothermia = Hypercalcemia$

axm55 : $\neg Hypothermia = NDS10$

axm56 : $\neg Hypercalcemia = NDS10$

END

An Event-B Specification of Step10_Miscellaneous_conditions
Generated Date: 25 Nov 2010 @ 03:39:47 PM

MACHINE Step10_Miscellaneous_conditions

REFINES Step9_Axis_Assessment_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

`ST_seg_ele` ST segment for elevation 1mm=0.1mV

`Disease_step4`

`Q_Width` Q wave width

`Q_Depth` Q wave depth

`Q_Normal_Status` Q wave normal or abnormal

`Age_of_Inf` Age of Infarct

`Disease_step5`

`Mice_State`

`R_Depth` R wave depth or height (also use in Step 7)

`R_Normal_Status` R wave normal or abnormal

`Q_Wave_State` Q wave states for all LEADS

`P_Wave_Peak` function to estimate the peak of LEADS signal

`Disease_step6`

`PP_Interval`

`RR_Interval`

`Diphasic`

`P_Wave_Broad`

`S_Depth` S wave depth or height

R_S_Ratio   R wave and S wave Ratio function

T_Wave_State   T wave patterns...

Disease_step8

T_Wave_State_B   B for alternative method of T wave assessment

T_Normal_Status   T wave normal or abnormal

Abnormal_Shaped_ST

Asy_T_Inversion_strain   Asymmetric T wave Inversion strain pattern

T_inversion   Deep T wave inversion

T_inversion_l_d   T inversion Localized and Diffuse

Disease_step8_B

QRS_Axis_State   QRS Axis Direction

minAngle   min. value of angle of Axis in degree

maxAngle   max. value of angle of Axis in degree

Axis_Devi   Axis Deviation in LEADS...

Disease_step9

Disease_step10

MC_Step10_Test_Needed   Miscellaneous Conditions test in Step 10

ST_depression

INVARIANTS

inv1 : $Disease\_step10 \in Misc\_Disease\_Codes\_Step10$

inv2 : $MC\_Step10\_Test\_Needed \in BOOL$

inv3 : $Sinus = Yes \land Disease\_step10 \in \{Incomplete\_RBBB, Pericarditis, Long\_QT, Hypokalemia, Digitalis\_toxicity, Electrical\_alternans, Electronic\_pacing, Hypothermia, Hypercalcemia\} \Rightarrow Heart\_State = KO$

inv4 : $Sinus = Yes \land Disease\_step9 = Dextrocardia \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : RR_Int_equidistant :∈ LEADS → BOOL
act2 : PP_Int_equidistant :∈ LEADS → BOOL
act3 : P_Positive :∈ LEADS → BOOL
act4 : Sinus := No
act5 : PP_Interval :∈ LEADS → ℕ
act6 : RR_Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → $\mathbb{N}_1$
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL

act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : *Disease_step10* := *NDS10*
act53 : *MC_Step10_Test_Needed* := *FALSE*

end

Event *Rhythm_test_TRUE* ≙
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any
rate

where
grd1 : (∃l·l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
RR_Int_equidistant(l) = TRUE ∧
RR_Interval(l) = PP_Interval(l))
∧
P_Positive(II) = TRUE

grd4 : rate ∈ 60 .. 100
60..100 is the range of normal heart rate
grd5 : PR_Int ≤ 200
Heart is Normal if PR ≤ 200 QRS_Int < 120
$HeartisNormalifQRS < 120$
grd6grd7 : Disease_step2 = NDS2
grd8 : Disease_step3 = NDS3
grd9 : Disease_step4 = NDS4
grd10 : Disease_step5 = NDS5
grd11 : Disease_step6 = NDS6
grd12 : Disease_step8 = NDS8
grd13 : Disease_step8_B = NDS8B
grd14 : Disease_step9 = NDS9
grd15 : *Disease_step10 = NDS10*

then

act1 : Sinus := Yes
act2 : Heart_Rate := rate
act3 : Heart_State := OK

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : (∀l·l ∈ {II, V1, V2} ⇒ PP_Int_equidistant(l) = FALSE ∨
RR_Int_equidistant(l) = FALSE ∨
RR_Interval(l) ≠ PP_Interval(l))
∨
P_Positive(II) = FALSE
grd2 : rate ∈ 1 .. 300

then

act1 : Sinus := No
act2 : Heart_Rate := rate
act3 : Heart_State := KO

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : (∃l·l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
RR_Int_equidistant(l) = TRUE ∧
RR_Interval(l) = PP_Interval(l))
∧
P_Positive(II) = TRUE

grd5 : $\texttt{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $\texttt{Disease\_step3} = \texttt{WPW\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{Brugada\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{RV\_Dysplasia} \lor \texttt{Disease\_step3} = \texttt{IVCD}$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\texttt{pr} \in 120 \,..\, 220$

time interval in (ms.)

grd2 : $\texttt{pr} > 200$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{PR\_Int} := \texttt{pr}$

act2 : $\texttt{Disease\_step2} := \texttt{First\_degree\_AV\_Block}$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{Notched\_R}(\texttt{I}) = \texttt{TRUE} \land \texttt{Notched\_R}(\texttt{V5}) = \texttt{TRUE} \land \texttt{Notched\_R}(\texttt{V6}) = \texttt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\texttt{Small\_R\_QS}(\texttt{V1}) = \texttt{TRUE} \land \texttt{Small\_R\_QS}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \land \texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \land \texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \land \texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$

from step 5

grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

from step 5

grd9 : $\mathtt{Axis\_Devi} = \mathtt{LAD} \wedge$
$\mathtt{minAngle} = -30 \wedge$
$\mathtt{maxAngle} = -90$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$
act2 : $\mathtt{Disease\_step2} := \mathtt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\mathtt{qrs} \in 50 \,..\, 150$
grd2 : $\mathtt{qrs} \geq 120$
grd3 : $\mathtt{Sinus} = \mathtt{Yes}$
grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd5 : $\mathtt{M\_Shape\_Complex}(\mathtt{V1}) = \mathtt{TRUE} \wedge$
$\mathtt{M\_Shape\_Complex}(\mathtt{V2}) = \mathtt{TRUE}$
grd7 : $\mathtt{Slurred\_S}(\mathtt{I}) = \mathtt{TRUE} \wedge$
$\mathtt{Slurred\_S}(\mathtt{V5}) = \mathtt{TRUE} \wedge$
$\mathtt{Slurred\_S}(\mathtt{V6}) = \mathtt{TRUE}$
grd8 : $\mathtt{Slurred\_S\_duration}(\mathtt{I}) > 40 \wedge$
$\mathtt{Slurred\_S\_duration}(\mathtt{V5}) > 40 \wedge$
$\mathtt{Slurred\_S\_duration}(\mathtt{V6}) > 40$

then

act1 : $\mathtt{QRS\_Int} := \mathtt{qrs}$
act2 : $\mathtt{Disease\_step2} := \mathtt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave
exmi

where

grd1 : $\mathtt{QRS\_Int} \geq 110$
grd2 : $\mathtt{sympt} = \mathtt{A\_RBBB} \vee \mathtt{sympt} = \mathtt{A\_LBBB}$
grd3 : $\mathtt{d\_wave} \in \mathbb{N}$
grd4 : $(\mathtt{d\_wave} + \mathtt{PR\_Int}) \leq 120$
Delta Wave + PR $\leq$ 120 Heart_State = KO
grd5grd6 : $\mathtt{Disease\_step4} = \mathtt{Acute\_inferior\_MI}$
grd7 : $\mathtt{exmi} \in \mathtt{Mice\_State5} \wedge \mathtt{exmi} = \mathtt{Exclude\_Mimics\_MI}$

then

act2 : $\mathtt{Delta\_Wave} := \mathtt{d\_wave}$
act3 : $\mathtt{Disease\_step3} := \mathtt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : $\mathtt{sympt} = \mathtt{A\_RBBB}$
grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd3 : $\mathtt{QRS\_Int} \geq 110$
grd4 : $\mathtt{Slurred\_S}(\mathtt{V5}) = \mathtt{FALSE} \wedge$
$\mathtt{Slurred\_S}(\mathtt{V6}) = \mathtt{FALSE}$
grd5 : $\mathtt{dis} \in \mathtt{Disease\_Codes\_Step3} \setminus \{\mathtt{WPW\_Syndrome}, \mathtt{NDS3}\}$
grd6 : $\mathtt{ST\_elevation}(\mathtt{V1}) = \mathtt{TRUE} \wedge$
$\mathtt{ST\_elevation}(\mathtt{V2}) = \mathtt{TRUE}$
grd7 : $\mathtt{Sinus} = \mathtt{Yes}$

then

act1 : $\mathtt{Disease\_step3} := \mathtt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : $\mathtt{sympt} = \mathtt{A\_RBBB}$
grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd3 : $\mathtt{QRS\_Int} \geq 110$
grd4 : $\mathtt{dis} \in \mathtt{Disease\_Codes\_Step3} \setminus \{\mathtt{WPW\_Syndrome}, \mathtt{Brugada\_Syndrome}, \mathtt{NDS3}\}$
grd5 : $\mathtt{Epsilon\_Wave}(\mathtt{V1}) = \mathtt{TRUE} \wedge$
$\mathtt{Epsilon\_Wave}(\mathtt{V3}) = \mathtt{TRUE}$

then

act1 : $\mathtt{Disease\_step3} := \mathtt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\mathtt{QRS\_Int} \geq 110$
grd2 : $\mathtt{dis} \in \mathtt{Disease\_Codes\_Step3} \setminus \{\mathtt{WPW\_Syndrome}, \mathtt{Brugada\_Syndrome}, \mathtt{RV\_Dysplasia}, \mathtt{NDS3}\}$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$

ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$

Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \in \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$

Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

$\texttt{grd1}: \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd2}: \texttt{Sinus} = \texttt{Yes}$

$\texttt{grd3}: \quad \vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

$\texttt{grd4}: \exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge\, \texttt{l} \neq \texttt{k}$

$\texttt{grd5}: \texttt{Disease\_step4} \notin \{\texttt{Troponin}, \texttt{CK\_MB}\}$

$\texttt{grd6}: \forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) < 5000$

$\texttt{grd7}: \texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

$\texttt{act1}: \texttt{Disease\_step4} := \texttt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *Q_Assessment_Normal*

when

$\texttt{grd1}: \texttt{Q\_Width}(\texttt{II}) < 40 \wedge \texttt{Q\_Depth}(\texttt{II}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVF}) < 40 \wedge \texttt{Q\_Depth}(\texttt{aVF}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVL}) < 40$

1000 micrometer= 1 milimeter

$\texttt{grd2}: \texttt{Q\_Width}(\texttt{III}) \leq 40 \wedge \texttt{Q\_Depth}(\texttt{III}) \leq 7000 \wedge \texttt{Q\_Depth}(\texttt{aVL}) \leq 7000$

$\texttt{grd3}: \texttt{Q\_Depth}(\texttt{I}) < 40 \wedge \texttt{Q\_Depth}(\texttt{I}) \leq 1500$

then

$\texttt{act1}: \texttt{Q\_Normal\_Status} := \texttt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$

Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

$\texttt{grd1}: \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd2}: \texttt{Sinus} = \texttt{Yes}$

$\texttt{grd3}: \quad \vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : $\texttt{Q\_Width(V5)} \geq 40 \land \texttt{Q\_Depth(V5)} > 3000 \land$
$\texttt{Q\_Width(V6)} \geq 40 \land \texttt{Q\_Depth(V6)} > 3000$
grd5 : $\texttt{Q\_Width(aVL)} \geq 40 \land \texttt{Q\_Depth(aVL)} > 7000$
grd6 : $\texttt{Q\_Depth(I)} \geq 40 \land \texttt{Q\_Depth(I)} > 1500$
grd7 : $\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Acute\_anterior\_MI}$

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$
Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$
grd2 : $\texttt{Sinus} = \texttt{Yes}$
grd3 : $\lor$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$
$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$
$\land$
$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$
$\land\, l1 \neq k1$
$\land$
$($
$(l1 = V1 \land k1 = V2) \lor$
$(l1 = V2 \land k1 = V3) \lor$
$(l1 = V3 \land k1 = V4) \lor$
$(l1 = V4 \land k1 = V5) \lor$
$(l1 = V5 \land k1 = V6)$
$)$
$))$
grd4 : $\texttt{Q\_Width(II)} \geq 40 \land \texttt{Q\_Depth(II)} > 3000 \land$
$\texttt{Q\_Width(III)} > 40 \land \texttt{Q\_Depth(III)} > 7000 \land$
$\texttt{Q\_Width(aVF)} \geq 40 \land \texttt{Q\_Depth(aVF)} > 3000$
grd5 : $\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Acute\_inferior\_MI}$

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$
$\lor$
$\texttt{Disease\_step5} \in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$
$\lor$
$\texttt{Mice\_State} = \texttt{Exclude\_Mimics\_MI}$
$\lor$
$\texttt{Disease\_step2} = \texttt{LBBB}$

then

act1 : $\texttt{Age\_of\_Inf} :\in \{\texttt{recent}, \texttt{old}, \texttt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd2 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act1 : $\texttt{Disease\_step5} := \texttt{Hypertrophic\_cardiomyopathy}$

act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth}(\texttt{V1}) \geq 0 \land \texttt{R\_Depth}(\texttt{V1}) \leq 6000 \land \texttt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth}(\texttt{V2}) > 200 \land \texttt{R\_Depth}(\texttt{V2}) \leq 12000$

grd3 : $\texttt{R\_Depth}(\texttt{V2}) \geq 1000 \land \texttt{R\_Depth}(\texttt{V2}) \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Mice\_State} :\in \{\texttt{late\_transition}, \texttt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{Q\_Wave\_State}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V2}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V3}) = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State}(\texttt{V4}) = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$

act2 : Mice_State := Exclude_Mimics_MI

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : Q_Wave_State(V5) = TRUE $\wedge$
Q_Wave_State(V6) = TRUE

grd2 : Heart_State = KO

then

act1 : Disease_step5 := Hypertrophic_cardiomyopathy

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : (P_Wave_Peak(II) < 3000 $\wedge$
P_Wave_Peak(V1) < 3000)
$\vee$
(P_Wave_Broad(II) < 110 $\wedge$ P_Wave_Broad(V1) < 110) $\vee$
Diphasic(II) = FALSE $\vee$
Diphasic(V1) = FALSE

then

act1 : Disease_step6 := NDS6

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : P_Wave_Peak(II) $\geq$ 3000

grd2 : P_Wave_Peak(V1) $\geq$ 3000

grd3 : Heart_State = KO

then

act1 : Disease_step6 := RAE

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes_Check_RAE*

when

grd1 : P_Wave_Peak(II) $\geq$ 3000

grd2 : P_Wave_Peak(V1) $\geq$ 3000

grd3 : Disease_step6 = RAE

grd4 : Heart_State = KO

then

act1 : Disease_step6 := RV_strain

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : $(\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \wedge \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \vee$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \vee$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{LAE}$

end

Event *P_Wave_assessment_Broad_Yes_Check_LAE* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes_Check_LAE*

when

grd1 : $(\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \wedge \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \vee$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \vee$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$

grd2 : $\texttt{Disease\_step6} = \texttt{LAE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} :\in \{\texttt{mitral\_stenosis}, \texttt{mitral\_regurgitation}, \texttt{LV\_failure}, \texttt{dilated\_cardiomyopathy}\}$

end

Event *LVH_Assessment* $\widehat{=}$

LVH Assessment

extends *LVH_Assessment*

any

LVH_specificity specificity in percentage

sensitivity sensitivity in percentage

sex

where

grd1 : $(\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \wedge \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \vee$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \vee$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$

grd2 : $\texttt{Disease\_step6} = \texttt{LAE}$

grd5 : $\texttt{sex} \in \{0, 1\}$

o for men and 1 for women

grd3 : $((\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V5})) > 35000$
$\vee$
$(\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V6})) > 35000)$

1mm = 1000 micrometer............. 1 assessment

grd4 : $((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 24000) \wedge \texttt{sex} = 0)$
$\vee$
$((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 18000) \wedge \texttt{sex} = 1)$

2 assessment

grd6 : $\texttt{LVH\_specificity} = 90$
$\wedge$
$\texttt{sensitivity} < 40$

1 and 2 assessment

grd7 : $\texttt{Disease\_step6} = \texttt{LAE} \Rightarrow \texttt{LVH\_specificity} < 98$

3 assesssment

grd8 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

A or B : from step 8 development

grd9 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd10 : $\texttt{Asy\_T\_Inversion\_strain(V5)} = \texttt{TRUE} \land$
$\texttt{Asy\_T\_Inversion\_strain(V6)} = \texttt{TRUE} \land$
$\texttt{Asy\_T\_Inversion\_strain(V4)} = \texttt{TRUE}$

grd11 : $\texttt{Heart\_State} = \texttt{KO}$

grd12 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

grd13 : $\texttt{Axis\_Devi} = \texttt{LAD} \land$
$\texttt{minAngle} = -30 \land$
$\texttt{maxAngle} = -90$

then

act1 : $\texttt{Disease\_step6} := \texttt{LVH\_cause}$

end

Event *RVH_Assessment* $\widehat{=}$

RVH Assessment

extends *RVH_Assessment*

any

age age od men or women

aixs axis for deviation

where

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$

grd4 : $\texttt{R\_Depth(V1)} \geq 7000 \land \texttt{age} > 30$

1 assessment

grd5 : $\texttt{S\_Depth(V5)} \geq 7000 \lor$
$\texttt{S\_Depth(V6)} \geq 7000$

2 assessment

grd6 : $\texttt{R\_S\_Ratio(V1)} \geq 100$

R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment

grd7 : $\texttt{R\_S\_Ratio(V5)} \leq 100$
$\lor$
$\texttt{R\_S\_Ratio(V6)} \leq 100$

4 assessment

grd8 : $\texttt{aixs} \in 0 \,..\, 360 \land \texttt{aixs} \geq 110$

5 assessment

grd9 : $\texttt{Disease\_step2} \notin \{\texttt{LBBB}, \texttt{RBBB}\}$

grd10 : $\texttt{QRS\_Int} < 120$

grd11 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

$AorB : fromstep8development$
$\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd12grd13 : $\mathtt{Asy\_T\_Inversion\_strain(V1) = TRUE} \land$
$\mathtt{Asy\_T\_Inversion\_strain(V2) = TRUE} \land$
$\mathtt{Asy\_T\_Inversion\_strain(V3) = TRUE}$

grd14 : $\mathtt{Heart\_State = KO}$

grd15 : $\mathtt{T\_Normal\_Status = FALSE}$

grd16 : $\mathtt{Axis\_Devi = RAD} \land$
$\mathtt{minAngle = 110} \land$
$\mathtt{maxAngle = 180}$

then

act1 : $\mathtt{Disease\_step6 := RVH}$

end

Event $T\_Wave\_Assessment\_Peaked\_V123456 \widehat{=}$
T Wave Assessment

refines $T\_Wave\_Assessment\_Peaked\_V123456$

when

grd1 : $\forall l \cdot l \in \{V1, V2, V3, V4, V5, V6\} \Rightarrow T\_Wave\_State(l) = Peaked$

grd2 : $MC\_Step10\_Test\_Needed = TRUE$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step8 := Hyperkalemia$

end

Event $T\_Wave\_Assessment\_Peaked\_V12 \widehat{=}$

extends $T\_Wave\_Assessment\_Peaked\_V12$

when

grd1 : $\mathtt{R\_Normal\_Status = FALSE}$

grd2 : $\mathtt{T\_Wave\_State(V1) = Peaked} \land$
$\mathtt{T\_Wave\_State(V2) = Peaked}$

grd3 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd4 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion(l)} < 5000$
step 8 B

$\texttt{grd5} : \texttt{T\_Normal\_Status} = \texttt{FALSE}$

$\texttt{grd6} :$ $\vee$

(Axis_Devi = RAD $\wedge$
$minAngle = 110 \wedge$
$maxAngle = 180$)

then

$\texttt{act1} : \texttt{Mice\_State} := \texttt{normal\_variant}$

end

Event *T_Wave_Assessment_Peaked_V12_MI* $\widehat{=}$
posterior MI using T wave assessment in LEADS V1 and V2

extends *T_Wave_Assessment_Peaked_V12_MI*

when

$\texttt{grd1} : \texttt{T\_Wave\_State}(\texttt{V1}) = \texttt{Peaked} \wedge$
$\texttt{T\_Wave\_State}(\texttt{V2}) = \texttt{Peaked}$

$\texttt{grd6} : \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd2} :$ $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

$\texttt{grd3} : \forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) > 5000$

$\texttt{grd4} : \texttt{T\_inversion\_l\_d}(\texttt{V2}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{V3}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{V4}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{V5}) = \texttt{Localized}$

$\texttt{grd5} : \texttt{T\_inversion\_l\_d}(\texttt{II}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{III}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{aVF}) = \texttt{Localized}$

$\texttt{grd7} : \texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

$\texttt{act1} : \texttt{Disease\_step8} := \texttt{posterior\_MI}$

end

Event *T_Wave_Assessment_Flat* $\widehat{=}$

extends *T_Wave_Assessment_Flat*

when

$\texttt{grd1} : \forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Flat}$

$\texttt{grd4} : \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd2} :$ $\vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

step 8 B

$\text{grd3}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) < 5000$
$\text{grd5}: \text{T\_Normal\_Status} = \text{FALSE}$

then

$\text{act1}: \text{Disease\_step8} := \text{Nonspecific\_ST\_T\_changes}$
$\text{act2}: \text{Disease\_step8\_B} :\in \{\text{Cardiomyopathy}, \text{Electrolyte\_depletion}, \text{Alcohol}, \text{Myocarditis}, \text{Other}\}$

end

Event *T_Wave_Assessment_Inverted_Yes* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_Yes*

when

$\text{grd1}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$
$\text{grd2}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{TRUE}$
$\lor$
$\text{Q\_Normal\_Status} = \text{FALSE}$
$\text{grd3}: \text{Heart\_State} = \text{KO}$

then

$\text{act1}: \text{Disease\_step8} :\in \{\text{Definite\_ischemia}, \text{Probable\_ischemia}, \text{Digitalis\_effect}\}$

end

Event *T_Wave_Assessment_Inverted_No* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_No*

when

$\text{grd1}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$
$\text{grd2}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{FALSE}$
$\lor$
$\text{Q\_Normal\_Status} = \text{TRUE}$
$\text{grd3}: \text{Heart\_State} = \text{KO}$

then

$\text{act1}: \text{Disease\_step8} := \text{Nonspecific}$

end

Event *T_Wave_Assessment_Inverted_Yes_PM* $\widehat{=}$

PM - pulmonary embolism this disease is already defined in previous development.

refines *T_Wave_Assessment_Inverted_Yes_PM*

when

$\text{grd1}: P\_Wave\_Peak(II) \geq 3000$
$\text{grd2}: P\_Wave\_Peak(V1) \geq 3000$
$\text{grd3}: Disease\_step6 = RAE$
$\text{grd4}: (\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

$A : step8$

$$\neg(\exists l, k \cdot l \in LEADS \land k \in LEADS \land$$
$$((ST\_seg\_ele(l) \geq 1000 \land ST\_seg\_ele(k) \geq 1000) \lor$$
$$(ST\_elevation(l) = TRUE \land ST\_elevation(k) = TRUE)$$
$$\lor$$
$$(Abnormal\_Shaped\_ST(l) = TRUE \land Abnormal\_Shaped\_ST(k) = TRUE))$$
$$\Rightarrow$$
$$l \neq k))$$

grd5grd6 : $Asy\_T\_Inversion\_strain(V1) = TRUE \wedge$
$Asy\_T\_Inversion\_strain(V2) = TRUE \wedge$
$Asy\_T\_Inversion\_strain(V3) = TRUE$

grd7 : $Axis\_Devi = RAD \wedge$
$minAngle = 110 \wedge$
$maxAngle = 180$

grd8 : $MC\_Step10\_Test\_Needed = TRUE$

grd9 : $Heart\_State = KO$

then

act1 : $Disease\_step6 := pulmonary\_embolism$

end

Event $T\_Wave\_Assessment\_B \widehat{=}$
B for alternate method of T wave assessment

extends $T\_Wave\_Assessment\_B$

when

grd1 : $\forall l \cdot l \in \{I, II, V3, V4, V5, V6\} \Rightarrow T\_Wave\_State\_B(l) = Upright$

grd2 : $T\_Wave\_State\_B(aVL) = Inverted\_B$

grd3 : $\forall l \cdot l \in \{III, aVL, aVF, V1, V2\} \Rightarrow T\_Wave\_State\_B(l) = Variable$

then

act1 : $T\_Normal\_Status := TRUE$

end

Event $T\_Wave\_Assessment\_B\_DI \widehat{=}$
abnormal T wave .....in B ...DI(Definite Ischemia)

extends $T\_Wave\_Assessment\_B\_DI$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$

grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE$

grd3 : $T\_Normal\_Status = FALSE$
added in step-8 B

grd5 : $Heart\_State = KO$

grd4 : $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$
$((ST\_seg\_ele(l) \geq 1000 \wedge ST\_seg\_ele(k) \geq 1000) \vee$
$(ST\_elevation(l) = TRUE \wedge ST\_elevation(k) = TRUE)$
$\vee$
$(Abnormal\_Shaped\_ST(l) = TRUE \wedge Abnormal\_Shaped\_ST(k) = TRUE))$
$\wedge$
$l \neq k$
added in step-8 B

then

act1 : $Disease\_step8 := Definite\_ischemia$

end

Event $T\_Inversion\_Likely\_Ischemia \widehat{=}$
probable Ischemia or Likly ischemia

extends $T\_Inversion\_Likely\_Ischemia$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$
grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE$
grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$
1 mm= 1000
grd4 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$
grd5 : $T\_inversion\_l\_d(V2) = Localized \wedge$
$T\_inversion\_l\_d(V3) = Localized \wedge$
$T\_inversion\_l\_d(V4) = Localized \wedge$
$T\_inversion\_l\_d(V5) = Localized$
grd6 : $T\_inversion\_l\_d(II) = Localized \wedge$
$T\_inversion\_l\_d(III) = Localized \wedge$
$T\_inversion\_l\_d(aVF) = Localized$
b. of Deep inversion ¿ 5mm
grd7 : $Heart\_State = KO$
grd8 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8 := Probable\_ischemia$

end

Event *T_Inversion_Diffuse_B* $\widehat{=}$
Step 8 B for c.

extends *T_Inversion_Diffuse_B*

when

grd1 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$
grd2 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$
grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion\_l\_d(l) = Diffuse$
grd4 : $Heart\_State = KO$
grd5 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8\_B :\in \{Cardiomyopathy, other\_nonspecific\}$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_less_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_less_40*

any

age

where

grd1 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Upright} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Upright}$

grd2 : $\texttt{age} \in \mathbb{N} \land \texttt{age} < 40$

then

act1 : $\texttt{minAngle} := 0$

act2 : $\texttt{maxAngle} := 110$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_gre_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_gre_40*

any

age

where

grd1 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Upright} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Upright}$

grd2 : $\texttt{age} \in \mathbb{N} \land \texttt{age} > 40$

then

act1 : $\texttt{minAngle} := -30$

act2 : $\texttt{maxAngle} := 90$

end

Event *Axis_Assessment_QRS_upright_No_QRS_positive* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_positive*

when

grd1 : $\neg(\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Upright} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Upright})$

grd2 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Positive} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Positive}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{minAngle} := -30$

act2 : $\texttt{maxAngle} := -90$

act3 : $\texttt{Axis\_Devi} := \texttt{LAD}$

end

Event *Axis_Assessment_QRS_upright_No_QRS_negative* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_negative*

when

grd1 : $\neg(\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Upright} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Upright})$

grd2 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Negative} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Negative}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{minAngle} := 110$

act2 : $\mathtt{maxAngle} := 180$

act3 : $\mathtt{Axis\_Devi} := \mathtt{RAD}$

end

Event *Misc_Disease_Step9_LAD* $\widehat{=}$

extends *Misc_Disease_Step9_LAD*

when

grd1 : $\mathtt{Axis\_Devi} = \mathtt{LAD} \land$
$\mathtt{minAngle} = -30 \land$
$\mathtt{maxAngle} = -90$

grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step9} :\in \{\mathtt{LAFB}, \mathtt{MSCHD}, \mathtt{Some\_Form\_VT}, \mathtt{ED\_OC}\}$

end

Event *Misc_Disease_Step9_RAD* $\widehat{=}$

refines *Misc_Disease_Step9_RAD*

when

grd1 : $Axis\_Devi = RAD \land$
$minAngle = 110 \land$
$maxAngle = 180$

grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step9 :\in \{LPFB, NV\_MSEC\}$

end

Event *R_Q_Assessment_R_Abnormal_V56_axis_deviation* $\widehat{=}$

extends *R_Q_Assessment_R_Abnormal_V56_axis_deviation*

when

grd1 : $\mathtt{Q\_Wave\_State(V5)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V6)} = \mathtt{TRUE}$

grd2 : $\mathtt{Axis\_Devi} = \mathtt{RAD} \land$
$\mathtt{minAngle} = 110 \land$
$\mathtt{maxAngle} = 180$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} := \mathtt{lateral\_MI}$

end

Event *Miscellaneous_Conditions_Step10* $\widehat{=}$

when

grd1 : $MC\_Step10\_Test\_Needed = TRUE$

grd2 : $Heart\_State = KO$

then

act1 : $Disease\_step10 :\in \{Incomplete\_RBBB, Pericarditis, Long\_QT, Hypokalemia, Digitalis\_toxicity, Electrical\_alternans, Electronic\_pacing, Hypothermia, Hypercalcemia\}$

end

Event $Misc\_Disease\_Step10\_Dextrcardia\_Test \ \widehat{=}$

refines $Misc\_Disease\_Step9\_RAD$

when

grd1 : $Axis\_Devi = RAD \land$
$minAngle = 110 \land$
$maxAngle = 180$

grd2 : $MC\_Step10\_Test\_Needed = TRUE$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step9 := Dextrocardia$

end

END

An Event-B Specification of Step11_ctx
Generated Date: 25 Nov 2010 @ 03:38:53 PM

CONTEXT Step11_ctx

SETS

`Disease_Codes_Step11`

`Disease_Codes_Step11_NW_QRS_T`

`NW_QRS_Tachycardia_RI` QRS Tachcardia Regular or Irregular State

CONSTANTS

`Atrial_Premature_Beats`

`Ventricular_Premature_Beats`

`Nodal_Premature_Beats`

`Bradyarrhythmias`

`Narrow_QRS_Tachycardias`

`Wide_QRS_Tachycardias`

`NDS11`

`Sinus_Tachycardia`

`AVNRT` Atrioventricular nodal reentrant tachycardia (AVNRT)

`AF_Fixed_AV_Conduction` Atrial flutter (with fixed AV conduction)

`AT_Paroxysmal_NParoxysmal` Atrial tachycardia (paroxysmal and nonparoxysmal)

`WPW_Syndrome_OCMT` WPW syndrome (orthodromic circus movement tachycardia)

`Atrail_Fibrillation`

`AF_Variable_AV_Conduction` Atrial flutter (with variable AV conduction)

`AT_Variable_AV_Block` Atrial tachycardia (variable AV block or Wenckebach)

`Multifocal_Atrial_Tachycardia`

`Ventricular_Tachycardia`

`Supraventricular_Tachycardia` Supraventricular tachycardia (with preexisting or functional bundle branch block)

`WPW_Syndrome_Orthodromic`

`Atrial_Tachycardia`

`WPW_Syndrome_Antidromic`

`AF_BBB_WPW_Synd_Antidromic` Atrial fibrillation (with bundle branch block or with WPW syndrome [antidromic])

`AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti` Atrial flutter (varying AV conduction, with bundle branch block or WPW syndrome [antidromic])

`Torsades_de_pointes`

`NDS11_NW_QRS`

`Regular`

`Irregular`

AXIOMS

axm1 : $Disease\_Codes\_Step11 = \{Atrial\_Premature\_Beats, Ventricular\_Premature\_Beats, Nodal\_Premature\_Beats, Bradyarrhythmias, Narrow\_QRS\_Tachycardias, Wide\_QRS\_Tachycardias, NDS11\}$

axm2 : $\neg Atrial\_Premature\_Beats = Ventricular\_Premature\_Beats$

$\texttt{axm3}: \neg Atrial\_Premature\_Beats = Nodal\_Premature\_Beats$

$\texttt{axm4}: \neg Atrial\_Premature\_Beats = Bradyarrhythmias$

$\texttt{axm5}: \neg Atrial\_Premature\_Beats = Narrow\_QRS\_Tachycardias$

$\texttt{axm6}: \neg Atrial\_Premature\_Beats = Wide\_QRS\_Tachycardias$

$\texttt{axm8}: \neg Atrial\_Premature\_Beats = NDS11$

$\texttt{axm9}: \neg Ventricular\_Premature\_Beats = Nodal\_Premature\_Beats$

$\texttt{axm10}: \neg Ventricular\_Premature\_Beats = Bradyarrhythmias$

$\texttt{axm11}: \neg Ventricular\_Premature\_Beats = Narrow\_QRS\_Tachycardias$

$\texttt{axm12}: \neg Ventricular\_Premature\_Beats = Wide\_QRS\_Tachycardias$

$\texttt{axm14}: \neg Ventricular\_Premature\_Beats = NDS11$

$\texttt{axm15}: \neg Nodal\_Premature\_Beats = Bradyarrhythmias$

$\texttt{axm16}: \neg Nodal\_Premature\_Beats = Narrow\_QRS\_Tachycardias$

$\texttt{axm17}: \neg Nodal\_Premature\_Beats = Wide\_QRS\_Tachycardias$

$\texttt{axm19}: \neg Nodal\_Premature\_Beats = NDS11$

$\texttt{axm20}: \neg Bradyarrhythmias = Narrow\_QRS\_Tachycardias$

$\texttt{axm21}: \neg Bradyarrhythmias = Wide\_QRS\_Tachycardias$

$\texttt{axm23}: \neg Bradyarrhythmias = NDS11$

$\texttt{axm24}: \neg Narrow\_QRS\_Tachycardias = Wide\_QRS\_Tachycardias$

$\texttt{axm26}: \neg Narrow\_QRS\_Tachycardias = NDS11$

$\texttt{axm28}: \neg Wide\_QRS\_Tachycardias = NDS11$

$\texttt{axm29}: Disease\_Codes\_Step11\_NW\_QRS\_T = \{Sinus\_Tachycardia, AVNRT,$
$AF\_Fixed\_AV\_Conduction, AT\_Paroxysmal\_NParoxysmal, WPW\_Syndrome\_OCMT,$
$Atrail\_Fibrillation, AF\_Variable\_AV\_Conduction, AT\_Variable\_AV\_Block,$
$Multifocal\_Atrial\_Tachycardia, Ventricular\_Tachycardia, Supraventricular\_Tachycardia,$
$WPW\_Syndrome\_Orthodromic, Atrial\_Tachycardia, WPW\_Syndrome\_Antidromic,$
$AF\_BBB\_WPW\_Synd\_Antidromic, AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti,$
$Torsades\_de\_pointes, NDS11\_NW\_QRS\}$

$\texttt{axm30}: \neg Sinus\_Tachycardia = AVNRT$

$\texttt{axm31}: \neg Sinus\_Tachycardia = AF\_Fixed\_AV\_Conduction$

$\texttt{axm32}: \neg Sinus\_Tachycardia = AT\_Paroxysmal\_NParoxysmal$

$\texttt{axm33}: \neg Sinus\_Tachycardia = WPW\_Syndrome\_OCMT$

$\texttt{axm34}: \neg Sinus\_Tachycardia = Atrail\_Fibrillation$

$\texttt{axm35}: \neg Sinus\_Tachycardia = AF\_Variable\_AV\_Conduction$

$\texttt{axm36}: \neg Sinus\_Tachycardia = AT\_Variable\_AV\_Block$

$\texttt{axm37}: \neg Sinus\_Tachycardia = Multifocal\_Atrial\_Tachycardia$

$\texttt{axm38}: \neg Sinus\_Tachycardia = Ventricular\_Tachycardia$

$\texttt{axm39}: \neg Sinus\_Tachycardia = Supraventricular\_Tachycardia$

$\texttt{axm40}: \neg Sinus\_Tachycardia = WPW\_Syndrome\_Orthodromic$

$\texttt{axm41}: \neg Sinus\_Tachycardia = Atrial\_Tachycardia$

$\texttt{axm42}: \neg Sinus\_Tachycardia = WPW\_Syndrome\_Antidromic$

$\texttt{axm43}: \neg Sinus\_Tachycardia = AF\_BBB\_WPW\_Synd\_Antidromic$

$\texttt{axm44}: \neg Sinus\_Tachycardia = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

$\texttt{axm45}: \neg Sinus\_Tachycardia = Torsades\_de\_pointes$

$\texttt{axm46}: \neg Sinus\_Tachycardia = NDS11\_NW\_QRS$

$\texttt{axm47}: \neg AVNRT = AF\_Fixed\_AV\_Conduction$

$\mathtt{axm48}: \neg AVNRT = AT\_Paroxysmal\_NParoxysmal$

$\mathtt{axm49}: \neg AVNRT = WPW\_Syndrome\_OCMT$

$\mathtt{axm50}: \neg AVNRT = Atrail\_Fibrillation$

$\mathtt{axm51}: \neg AVNRT = AF\_Variable\_AV\_Conduction$

$\mathtt{axm52}: \neg AVNRT = AT\_Variable\_AV\_Block$

$\mathtt{axm53}: \neg AVNRT = Multifocal\_Atrial\_Tachycardia$

$\mathtt{axm54}: \neg AVNRT = Ventricular\_Tachycardia$

$\mathtt{axm55}: \neg AVNRT = Supraventricular\_Tachycardia$

$\mathtt{axm56}: \neg AVNRT = WPW\_Syndrome\_Orthodromic$

$\mathtt{axm57}: \neg AVNRT = Atrial\_Tachycardia$

$\mathtt{axm58}: \neg AVNRT = WPW\_Syndrome\_Antidromic$

$\mathtt{axm59}: \neg AVNRT = AF\_BBB\_WPW\_Synd\_Antidromic$

$\mathtt{axm60}: \neg AVNRT = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

$\mathtt{axm61}: \neg AVNRT = Torsades\_de\_pointes$

$\mathtt{axm62}: \neg AVNRT = NDS11\_NW\_QRS$

$\mathtt{axm63}: \neg AF\_Fixed\_AV\_Conduction = AT\_Paroxysmal\_NParoxysmal$

$\mathtt{axm64}: \neg AF\_Fixed\_AV\_Conduction = WPW\_Syndrome\_OCMT$

$\mathtt{axm65}: \neg AF\_Fixed\_AV\_Conduction = Atrail\_Fibrillation$

$\mathtt{axm66}: \neg AF\_Fixed\_AV\_Conduction = AF\_Variable\_AV\_Conduction$

$\mathtt{axm67}: \neg AF\_Fixed\_AV\_Conduction = AT\_Variable\_AV\_Block$

$\mathtt{axm68}: \neg AF\_Fixed\_AV\_Conduction = Multifocal\_Atrial\_Tachycardia$

$\mathtt{axm69}: \neg AF\_Fixed\_AV\_Conduction = Ventricular\_Tachycardia$

$\mathtt{axm70}: \neg AF\_Fixed\_AV\_Conduction = Supraventricular\_Tachycardia$

$\mathtt{axm71}: \neg AF\_Fixed\_AV\_Conduction = WPW\_Syndrome\_Orthodromic$

$\mathtt{axm72}: \neg AF\_Fixed\_AV\_Conduction = Atrial\_Tachycardia$

$\mathtt{axm73}: \neg AF\_Fixed\_AV\_Conduction = WPW\_Syndrome\_Antidromic$

$\mathtt{axm74}: \neg AF\_Fixed\_AV\_Conduction = AF\_BBB\_WPW\_Synd\_Antidromic$

$\mathtt{axm75}: \neg AF\_Fixed\_AV\_Conduction = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

$\mathtt{axm76}: \neg AF\_Fixed\_AV\_Conduction = Torsades\_de\_pointes$

$\mathtt{axm77}: \neg AF\_Fixed\_AV\_Conduction = NDS11\_NW\_QRS$

$\mathtt{axm78}: \neg AT\_Paroxysmal\_NParoxysmal = WPW\_Syndrome\_OCMT$

$\mathtt{axm79}: \neg AT\_Paroxysmal\_NParoxysmal = Atrail\_Fibrillation$

$\mathtt{axm80}: \neg AT\_Paroxysmal\_NParoxysmal = AF\_Variable\_AV\_Conduction$

$\mathtt{axm81}: \neg AT\_Paroxysmal\_NParoxysmal = AT\_Variable\_AV\_Block$

$\mathtt{axm82}: \neg AT\_Paroxysmal\_NParoxysmal = Multifocal\_Atrial\_Tachycardia$

$\mathtt{axm83}: \neg AT\_Paroxysmal\_NParoxysmal = Ventricular\_Tachycardia$

$\mathtt{axm84}: \neg AT\_Paroxysmal\_NParoxysmal = Supraventricular\_Tachycardia$

$\mathtt{axm85}: \neg AT\_Paroxysmal\_NParoxysmal = WPW\_Syndrome\_Orthodromic$

$\mathtt{axm86}: \neg AT\_Paroxysmal\_NParoxysmal = Atrial\_Tachycardia$

$\mathtt{axm87}: \neg AT\_Paroxysmal\_NParoxysmal = WPW\_Syndrome\_Antidromic$

$\mathtt{axm88}: \neg AT\_Paroxysmal\_NParoxysmal = AF\_BBB\_WPW\_Synd\_Antidromic$

$\mathtt{axm89}: \neg AT\_Paroxysmal\_NParoxysmal = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

$\mathtt{axm90}: \neg AT\_Paroxysmal\_NParoxysmal = Torsades\_de\_pointes$

$\mathtt{axm91}: \neg AT\_Paroxysmal\_NParoxysmal = NDS11\_NW\_QRS$

$\text{axm92}: \neg WPW\_Syndrome\_OCMT = Atrail\_Fibrillation$

$\text{axm93}: \neg WPW\_Syndrome\_OCMT = AF\_Variable\_AV\_Conduction$

$\text{axm94}: \neg WPW\_Syndrome\_OCMT = AT\_Variable\_AV\_Block$

$\text{axm95}: \neg WPW\_Syndrome\_OCMT = Multifocal\_Atrial\_Tachycardia$

$\text{axm96}: \neg WPW\_Syndrome\_OCMT = Ventricular\_Tachycardia$

$\text{axm97}: \neg WPW\_Syndrome\_OCMT = Supraventricular\_Tachycardia$

$\text{axm98}: \neg WPW\_Syndrome\_OCMT = WPW\_Syndrome\_Orthodromic$

$\text{axm99}: \neg WPW\_Syndrome\_OCMT = Atrial\_Tachycardia$

$\text{axm100}: \neg WPW\_Syndrome\_OCMT = WPW\_Syndrome\_Antidromic$

$\text{axm101}: \neg WPW\_Syndrome\_OCMT = AF\_BBB\_WPW\_Synd\_Antidromic$

$\text{axm102}: \neg WPW\_Syndrome\_OCMT = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

$\text{axm103}: \neg WPW\_Syndrome\_OCMT = Torsades\_de\_pointes$

$\text{axm104}: \neg WPW\_Syndrome\_OCMT = NDS11\_NW\_QRS$

$\text{axm105}: \neg Atrail\_Fibrillation = AF\_Variable\_AV\_Conduction$

$\text{axm106}: \neg Atrail\_Fibrillation = AT\_Variable\_AV\_Block$

$\text{axm107}: \neg Atrail\_Fibrillation = Multifocal\_Atrial\_Tachycardia$

$\text{axm108}: \neg Atrail\_Fibrillation = Ventricular\_Tachycardia$

$\text{axm109}: \neg Atrail\_Fibrillation = Supraventricular\_Tachycardia$

$\text{axm110}: \neg Atrail\_Fibrillation = WPW\_Syndrome\_Orthodromic$

$\text{axm111}: \neg Atrail\_Fibrillation = Atrial\_Tachycardia$

$\text{axm112}: \neg Atrail\_Fibrillation = WPW\_Syndrome\_Antidromic$

$\text{axm113}: \neg Atrail\_Fibrillation = AF\_BBB\_WPW\_Synd\_Antidromic$

$\text{axm114}: \neg Atrail\_Fibrillation = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

$\text{axm115}: \neg Atrail\_Fibrillation = Torsades\_de\_pointes$

$\text{axm116}: \neg Atrail\_Fibrillation = NDS11\_NW\_QRS$

$\text{axm117}: \neg AF\_Variable\_AV\_Conduction = AT\_Variable\_AV\_Block$

$\text{axm118}: \neg AF\_Variable\_AV\_Conduction = Multifocal\_Atrial\_Tachycardia$

$\text{axm119}: \neg AF\_Variable\_AV\_Conduction = Ventricular\_Tachycardia$

$\text{axm120}: \neg AF\_Variable\_AV\_Conduction = Supraventricular\_Tachycardia$

$\text{axm121}: \neg AF\_Variable\_AV\_Conduction = WPW\_Syndrome\_Orthodromic$

$\text{axm122}: \neg AF\_Variable\_AV\_Conduction = Atrial\_Tachycardia$

$\text{axm123}: \neg AF\_Variable\_AV\_Conduction = WPW\_Syndrome\_Antidromic$

$\text{axm124}: \neg AF\_Variable\_AV\_Conduction = AF\_BBB\_WPW\_Synd\_Antidromic$

$\text{axm125}: \neg AF\_Variable\_AV\_Conduction = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

$\text{axm126}: \neg AF\_Variable\_AV\_Conduction = Torsades\_de\_pointes$

$\text{axm127}: \neg AF\_Variable\_AV\_Conduction = NDS11\_NW\_QRS$

$\text{axm128}: \neg AT\_Variable\_AV\_Block = Multifocal\_Atrial\_Tachycardia$

$\text{axm129}: \neg AT\_Variable\_AV\_Block = Ventricular\_Tachycardia$

$\text{axm130}: \neg AT\_Variable\_AV\_Block = Supraventricular\_Tachycardia$

$\text{axm131}: \neg AT\_Variable\_AV\_Block = WPW\_Syndrome\_Orthodromic$

$\text{axm132}: \neg AT\_Variable\_AV\_Block = Atrial\_Tachycardia$

$\text{axm133}: \neg AT\_Variable\_AV\_Block = WPW\_Syndrome\_Antidromic$

$\text{axm134}: \neg AT\_Variable\_AV\_Block = AF\_BBB\_WPW\_Synd\_Antidromic$

$\text{axm135}: \neg AT\_Variable\_AV\_Block = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm136 : $\neg AT\_Variable\_AV\_Block = Torsades\_de\_pointes$

axm137 : $\neg AT\_Variable\_AV\_Block = NDS11\_NW\_QRS$

axm138 : $\neg Multifocal\_Atrial\_Tachycardia = Ventricular\_Tachycardia$

axm139 : $\neg Multifocal\_Atrial\_Tachycardia = Supraventricular\_Tachycardia$

axm140 : $\neg Multifocal\_Atrial\_Tachycardia = WPW\_Syndrome\_Orthodromic$

axm141 : $\neg Multifocal\_Atrial\_Tachycardia = Atrial\_Tachycardia$

axm142 : $\neg Multifocal\_Atrial\_Tachycardia = WPW\_Syndrome\_Antidromic$

axm143 : $\neg Multifocal\_Atrial\_Tachycardia = AF\_BBB\_WPW\_Synd\_Antidromic$

axm144 : $\neg Multifocal\_Atrial\_Tachycardia = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm145 : $\neg Multifocal\_Atrial\_Tachycardia = Torsades\_de\_pointes$

axm146 : $\neg Multifocal\_Atrial\_Tachycardia = NDS11\_NW\_QRS$

axm147 : $\neg Ventricular\_Tachycardia = Supraventricular\_Tachycardia$

axm148 : $\neg Ventricular\_Tachycardia = WPW\_Syndrome\_Orthodromic$

axm149 : $\neg Ventricular\_Tachycardia = Atrial\_Tachycardia$

axm150 : $\neg Ventricular\_Tachycardia = WPW\_Syndrome\_Antidromic$

axm151 : $\neg Ventricular\_Tachycardia = AF\_BBB\_WPW\_Synd\_Antidromic$

axm152 : $\neg Ventricular\_Tachycardia = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm153 : $\neg Ventricular\_Tachycardia = Torsades\_de\_pointes$

axm154 : $\neg Ventricular\_Tachycardia = NDS11\_NW\_QRS$

axm155 : $\neg Supraventricular\_Tachycardia = WPW\_Syndrome\_Orthodromic$

axm156 : $\neg Supraventricular\_Tachycardia = Atrial\_Tachycardia$

axm157 : $\neg Supraventricular\_Tachycardia = WPW\_Syndrome\_Antidromic$

axm158 : $\neg Supraventricular\_Tachycardia = AF\_BBB\_WPW\_Synd\_Antidromic$

axm159 : $\neg Supraventricular\_Tachycardia = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm160 : $\neg Supraventricular\_Tachycardia = Torsades\_de\_pointes$

axm161 : $\neg Supraventricular\_Tachycardia = NDS11\_NW\_QRS$

axm162 : $\neg WPW\_Syndrome\_Orthodromic = Atrial\_Tachycardia$

axm163 : $\neg WPW\_Syndrome\_Orthodromic = WPW\_Syndrome\_Antidromic$

axm164 : $\neg WPW\_Syndrome\_Orthodromic = AF\_BBB\_WPW\_Synd\_Antidromic$

axm165 : $\neg WPW\_Syndrome\_Orthodromic = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm166 : $\neg WPW\_Syndrome\_Orthodromic = Torsades\_de\_pointes$

axm167 : $\neg WPW\_Syndrome\_Orthodromic = NDS11\_NW\_QRS$

axm168 : $\neg Atrial\_Tachycardia = WPW\_Syndrome\_Antidromic$

axm169 : $\neg Atrial\_Tachycardia = AF\_BBB\_WPW\_Synd\_Antidromic$

axm170 : $\neg Atrial\_Tachycardia = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm171 : $\neg Atrial\_Tachycardia = Torsades\_de\_pointes$

axm172 : $\neg Atrial\_Tachycardia = NDS11\_NW\_QRS$

axm173 : $\neg WPW\_Syndrome\_Antidromic = AF\_BBB\_WPW\_Synd\_Antidromic$

axm174 : $\neg WPW\_Syndrome\_Antidromic = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm175 : $\neg WPW\_Syndrome\_Antidromic = Torsades\_de\_pointes$

axm176 : $\neg WPW\_Syndrome\_Antidromic = NDS11\_NW\_QRS$

axm177 : $\neg AF\_BBB\_WPW\_Synd\_Antidromic = AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti$

axm178 : $\neg AF\_BBB\_WPW\_Synd\_Antidromic = Torsades\_de\_pointes$

axm179 : $\neg AF\_BBB\_WPW\_Synd\_Antidromic = NDS11\_NW\_QRS$

$\texttt{axm180}: \neg AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti = Torsades\_de\_pointes$

$\texttt{axm181}: \neg AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti = NDS11\_NW\_QRS$

$\texttt{axm182}: \neg Torsades\_de\_pointes = NDS11\_NW\_QRS$

$\texttt{axm183}: NW\_QRS\_Tachycardia\_RI = \{Regular, Irregular\}$

$\texttt{axm184}: \neg Regular = Irregular$

END

An Event-B Specification of Step_11_Abnormal_Rhythm
Generated Date: 25 Nov 2010 @ 03:39:50 PM

MACHINE Step_11_Abnormal_Rhythm

REFINES Step10_Miscellaneous_conditions

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx, Step11_ctx

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

`ST_seg_ele` ST segment for elevation 1mm=0.1mV

`Disease_step4`

`Q_Width` Q wave width

`Q_Depth` Q wave depth

`Q_Normal_Status` Q wave normal or abnormal

`Age_of_Inf` Age of Infarct

`Disease_step5`

`Mice_State`

`R_Depth` R wave depth or height (also use in Step 7)

`R_Normal_Status` R wave normal or abnormal

`Q_Wave_State` Q wave states for all LEADS

`P_Wave_Peak` function to estimate the peak of LEADS signal

`Disease_step6`

`PP_Interval`

`RR_Interval`

`Diphasic`

`P_Wave_Broad`

S_Depth   S wave depth or height

R_S_Ratio   R wave and S wave Ratio function

T_Wave_State   T wave patterns...

Disease_step8

T_Wave_State_B   B for alternative method of T wave assessment

T_Normal_Status   T wave normal or abnormal

Abnormal_Shaped_ST

Asy_T_Inversion_strain   Asymmetric T wave Inversion strain pattern

T_inversion   Deep T wave inversion

T_inversion_l_d   T inversion Localized and Diffuse

Disease_step8_B

QRS_Axis_State   QRS Axis Direction

minAngle   min. value of angle of Axis in degree

maxAngle   max. value of angle of Axis in degree

Axis_Devi   Axis Deviation in LEADS...

Disease_step9

Disease_step10

MC_Step10_Test_Needed   Miscellaneous Conditions test in Step 10

Disease_step11

ST_depression

INVARIANTS

inv1 : $Disease\_step11 \in Disease\_Codes\_Step11$

inv2 : $Sinus = Yes \land Disease\_step11 \in \{Atrial\_Premature\_Beats, Ventricular\_Premature\_Beats, Nodal\_Premature\_Beats, Bradyarrhythmias, Narrow\_QRS\_Tachycardias, Wide\_QRS\_Tachycardias\} \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : RR_Int_equidistant :∈ LEADS → BOOL

act2 : PP_Int_equidistant :∈ LEADS → BOOL

act3 : P_Positive :∈ LEADS → BOOL

act4 : Sinus := No

act5 : PP_Interval :∈ LEADS → ℕ

act6 : RR_Interval :∈ LEADS → ℕ

act7 : Heart_Rate :∈ 1 .. 300

act8 : Heart_State := KO

act9 : PR_Int := 120

act10 : Disease_step2 := NDS2

act11 : QRS_Int := 50

act12 : Notched_R :∈ LEADS → BOOL

act13 : Small_R_QS :∈ LEADS → BOOL

act14 : Slurred_S_duration :∈ LEADS → $\mathbb{N}_1$

act15 : M_Shape_Complex :∈ LEADS → BOOL

act16 : Slurred_S :∈ LEADS → BOOL

act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : Disease_step10 := NDS10
act53 : MC_Step10_Test_Needed := FALSE
act54 : *Disease_step11* := *NDS11*

end

Event *Rhythm_test_TRUE* ≙
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any
rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd4 : $rate \in 60 .. 100$
60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$
Heart is Normal if PR $\leq$ 200 QRS_Int < 120
$HeartisNormalifQRS < 120$

grd6grd7 : $Disease\_step2 = NDS2$

grd8 : $Disease\_step3 = NDS3$

grd9 : $Disease\_step4 = NDS4$

grd10 : $Disease\_step5 = NDS5$

grd11 : $Disease\_step6 = NDS6$

grd12 : $Disease\_step8 = NDS8$

grd13 : $Disease\_step8\_B = NDS8B$

grd14 : $Disease\_step9 = NDS9$

grd15 : $Disease\_step10 = NDS10$

grd16 : $Disease\_step11 = NDS11$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $rate \in 1 .. 300$

then

act1 : $Sinus := No$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd5 : $rate \in 1 .. 300 \setminus 60 .. 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $Disease\_step3 = WPW\_Syndrome \lor Disease\_step3 = Brugada\_Syndrome \lor$
$Disease\_step3 = RV\_Dysplasia \lor Disease\_step3 = IVCD$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $pr \in 120 .. 220$
time interval in (ms.)

grd2 : $pr > 200$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

then

act1 : $PR\_Int := pr$

act2 : $Disease\_step2 := First\_degree\_AV\_Block$

end

Event *QRS_Test_LBBB* $\widehat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $qrs \in 50 .. 150$

grd2 : $qrs \geq 120$

grd3 : $Sinus = Yes$

grd4 : $Heart\_State = KO$

grd5 : $Notched\_R(I) = TRUE \land$
$Notched\_R(V5) = TRUE \land$
$Notched\_R(V6) = TRUE$
Right Bundle Branch Block (RBBB)

grd6 : $Small\_R\_QS(V1) = TRUE \land$
$Small\_R\_QS(V2) = TRUE$

grd7 : $\texttt{Q\_Wave\_State(V1)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V2)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V3)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V4)} = \texttt{TRUE}$
from step 5

grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$
from step 5

grd9 : $\texttt{Axis\_Devi} = \texttt{LAD} \land$
$\texttt{minAngle} = -30 \land$
$\texttt{maxAngle} = -90$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$
Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex(V1)} = \texttt{TRUE} \land$
$\texttt{M\_Shape\_Complex(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S(I)} = \texttt{TRUE} \land$
$\texttt{Slurred\_S(V5)} = \texttt{TRUE} \land$
$\texttt{Slurred\_S(V6)} = \texttt{TRUE}$

grd8 : $\texttt{Slurred\_S\_duration(I)} > 40 \land$
$\texttt{Slurred\_S\_duration(V5)} > 40 \land$
$\texttt{Slurred\_S\_duration(V6)} > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt

d_wave

exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \lor \texttt{sympt} = \texttt{A\_LBBB}$

grd3 : $\texttt{d\_wave} \in \mathbb{N}$

grd4 : $(\mathtt{d\_wave} + \mathtt{PR\_Int}) \leq 120$
Delta Wave + PR $\leq$ 120 `Heart_State = KO`
grd5grd6 : $\mathtt{Disease\_step4} = \mathtt{Acute\_inferior\_MI}$
grd7 : $\mathtt{exmi} \in \mathtt{Mice\_State5} \land \mathtt{exmi} = \mathtt{Exclude\_Mimics\_MI}$

then

act2 : $\mathtt{Delta\_Wave} := \mathtt{d\_wave}$
act3 : $\mathtt{Disease\_step3} := \mathtt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : $\mathtt{sympt} = \mathtt{A\_RBBB}$
grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd3 : $\mathtt{QRS\_Int} \geq 110$
grd4 : $\mathtt{Slurred\_S}(\mathtt{V5}) = \mathtt{FALSE} \land$
$\mathtt{Slurred\_S}(\mathtt{V6}) = \mathtt{FALSE}$
grd5 : $\mathtt{dis} \in \mathtt{Disease\_Codes\_Step3} \setminus \{\mathtt{WPW\_Syndrome}, \mathtt{NDS3}\}$
grd6 : $\mathtt{ST\_elevation}(\mathtt{V1}) = \mathtt{TRUE} \land$
$\mathtt{ST\_elevation}(\mathtt{V2}) = \mathtt{TRUE}$
grd7 : $\mathtt{Sinus} = \mathtt{Yes}$

then

act1 : $\mathtt{Disease\_step3} := \mathtt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : $\mathtt{sympt} = \mathtt{A\_RBBB}$
grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd3 : $\mathtt{QRS\_Int} \geq 110$
grd4 : $\mathtt{dis} \in \mathtt{Disease\_Codes\_Step3} \setminus \{\mathtt{WPW\_Syndrome}, \mathtt{Brugada\_Syndrome}, \mathtt{NDS3}\}$
grd5 : $\mathtt{Epsilon\_Wave}(\mathtt{V1}) = \mathtt{TRUE} \land$
$\mathtt{Epsilon\_Wave}(\mathtt{V3}) = \mathtt{TRUE}$

then

act1 : $\mathtt{Disease\_step3} := \mathtt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

`dis`

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$

ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\lor$

$$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$$
$$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$$
$$\land$$
$$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$$
$$\land\, l1 \neq k1$$
$$\land$$
$$($$
$$(l1 = V1 \land k1 = V2) \lor$$
$$(l1 = V2 \land k1 = V3) \lor$$
$$(l1 = V3 \land k1 = V4) \lor$$
$$(l1 = V4 \land k1 = V5) \lor$$
$$(l1 = V5 \land k1 = V6)$$
$$)$$
$$))$$

grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$

Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\lor$

$$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$$
$$(ST\_elevation(l1) = FALSE \land ST\_seg\_ele(l1) < 1000))$$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \land \texttt{k} \in \texttt{LEADS} \land$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \land \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\land\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \in \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$
Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \notin \{\texttt{Troponin}, \texttt{CK\_MB}\}$

grd6 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) < 5000$

grd7 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : $\texttt{Q\_Width}(\texttt{II}) < 40 \wedge \texttt{Q\_Depth}(\texttt{II}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVF}) < 40 \wedge \texttt{Q\_Depth}(\texttt{aVF}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVL}) < 40$

1000 micrometer= 1 milimeter

grd2 : $\texttt{Q\_Width}(\texttt{III}) \leq 40 \wedge \texttt{Q\_Depth}(\texttt{III}) \leq 7000 \wedge \texttt{Q\_Depth}(\texttt{aVL}) \leq 7000$

grd3 : $\texttt{Q\_Depth}(\texttt{I}) < 40 \wedge \texttt{Q\_Depth}(\texttt{I}) \leq 1500$

then

act1 : $\texttt{Q\_Normal\_Status} := \texttt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$

$\wedge$
(
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
)
))

grd4 : $\texttt{Q\_Width(V5)} \geq 40 \wedge \texttt{Q\_Depth(V5)} > 3000 \wedge$
$\texttt{Q\_Width(V6)} \geq 40 \wedge \texttt{Q\_Depth(V6)} > 3000$

grd5 : $\texttt{Q\_Width(aVL)} \geq 40 \wedge \texttt{Q\_Depth(aVL)} > 7000$

grd6 : $\texttt{Q\_Depth(I)} \geq 40 \wedge \texttt{Q\_Depth(I)} > 1500$

grd7 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_anterior_MI

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$
Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge l1 \neq k1$
$\wedge$
(
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
)
))

grd4 : $\texttt{Q\_Width(II)} \geq 40 \wedge \texttt{Q\_Depth(II)} > 3000 \wedge$
$\texttt{Q\_Width(III)} > 40 \wedge \texttt{Q\_Depth(III)} > 7000 \wedge$
$\texttt{Q\_Width(aVF)} \geq 40 \wedge \texttt{Q\_Depth(aVF)} > 3000$

grd5 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_inferior_MI

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\text{Disease\_step4} = \text{Acute\_inferior\_MI}$
$\lor$
$\text{Disease\_step5} \in \{\text{anterior\_MI}, \text{LVH}, \text{emphysema}\}$
$\lor$
$\text{Mice\_State} = \text{Exclude\_Mimics\_MI}$
$\lor$
$\text{Disease\_step2} = \text{LBBB}$

then

act1 : $\text{Age\_of\_Inf} :\in \{\text{recent}, \text{old}, \text{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\text{Disease\_step4} = \text{Acute\_inferior\_MI}$

grd2 : $\text{exmi} \in \text{Mice\_State5} \land \text{exmi} = \text{Exclude\_Mimics\_MI}$

then

act1 : $\text{Disease\_step5} := \text{Hypertrophic\_cardiomyopathy}$

act2 : $\text{Mice\_State} := \text{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\text{R\_Depth}(\text{V1}) \geq 0 \land \text{R\_Depth}(\text{V1}) \leq 6000 \land \text{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\text{R\_Depth}(\text{V2}) > 200 \land \text{R\_Depth}(\text{V2}) \leq 12000$

grd3 : $\text{R\_Depth}(\text{V2}) \geq 1000 \land \text{R\_Depth}(\text{V2}) \leq 24000$

then

act1 : $\text{R\_Normal\_Status} := \text{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\text{R\_Normal\_Status} = \text{FALSE}$

then

act1 : $\text{Mice\_State} :\in \{\text{late\_transition}, \text{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$

grd2 : $\mathtt{Q\_Wave\_State}(\mathtt{V1}) = \mathtt{TRUE} \wedge$
$\mathtt{Q\_Wave\_State}(\mathtt{V2}) = \mathtt{TRUE} \wedge$
$\mathtt{Q\_Wave\_State}(\mathtt{V3}) = \mathtt{TRUE} \wedge$
$\mathtt{Q\_Wave\_State}(\mathtt{V4}) = \mathtt{TRUE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} :\in \{\mathtt{anterior\_MI}, \mathtt{LVH}, \mathtt{emphysema}\}$

act2 : $\mathtt{Mice\_State} := \mathtt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\mathtt{Q\_Wave\_State}(\mathtt{V5}) = \mathtt{TRUE} \wedge$
$\mathtt{Q\_Wave\_State}(\mathtt{V6}) = \mathtt{TRUE}$

grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} := \mathtt{Hypertrophic\_cardiomyopathy}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $(\mathtt{P\_Wave\_Peak}(\mathtt{II}) < 3000 \wedge$
$\mathtt{P\_Wave\_Peak}(\mathtt{V1}) < 3000)$
$\vee$
$(\mathtt{P\_Wave\_Broad}(\mathtt{II}) < 110 \wedge \mathtt{P\_Wave\_Broad}(\mathtt{V1}) < 110) \vee$
$\mathtt{Diphasic}(\mathtt{II}) = \mathtt{FALSE} \vee$
$\mathtt{Diphasic}(\mathtt{V1}) = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : $\mathtt{P\_Wave\_Peak}(\mathtt{II}) \geq 3000$

grd2 : $\mathtt{P\_Wave\_Peak}(\mathtt{V1}) \geq 3000$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RAE}$

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes_Check_RAE*

when

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{RV\_strain}$

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \land \texttt{P\_Wave\_Broad(V1)} \geq 110) \lor$
$\texttt{Diphasic(II)} = \texttt{TRUE} \lor$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{LAE}$

end

Event *P_Wave_assessment_Broad_Yes_Check_LAE* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes_Check_LAE*

when

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \land \texttt{P\_Wave\_Broad(V1)} \geq 110) \lor$
$\texttt{Diphasic(II)} = \texttt{TRUE} \lor$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Disease\_step6} = \texttt{LAE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} :\in \{\texttt{mitral\_stenosis}, \texttt{mitral\_regurgitation},$
$\texttt{LV\_failure}, \texttt{dilated\_cardiomyopathy}\}$

end

Event *LVH_Assessment* $\widehat{=}$
LVH Assessment

extends *LVH_Assessment*

any

`LVH_specificity` specificity in percentage

`sensitivity` sensitivity in percentage

`sex`

where

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \land \texttt{P\_Wave\_Broad(V1)} \geq 110) \lor$
$\texttt{Diphasic(II)} = \texttt{TRUE} \lor$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Disease\_step6} = \texttt{LAE}$

grd5 : $\texttt{sex} \in \{0, 1\}$
o for men and 1 for women

grd3 : $((\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V5})) > 35000$
$\vee$
$(\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V6})) > 35000)$
1mm = 1000 micrometer............. 1 assessment
grd4 : $((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 24000) \wedge \texttt{sex} = 0)$
$\vee$
$((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 18000) \wedge \texttt{sex} = 1)$
2 assessment
grd6 : $\texttt{LVH\_specificity} = 90$
$\wedge$
$\texttt{sensitivity} < 40$
1 and 2 assessment
grd7 : $\texttt{Disease\_step6} = \texttt{LAE} \Rightarrow \texttt{LVH\_specificity} < 98$
3 assesssment
grd8 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$
A or B : from step 8 development
grd9 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$
grd10 : $\texttt{Asy\_T\_Inversion\_strain}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain}(\texttt{V6}) = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain}(\texttt{V4}) = \texttt{TRUE}$
grd11 : $\texttt{Heart\_State} = \texttt{KO}$
grd12 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$
grd13 : $\texttt{Axis\_Devi} = \texttt{LAD} \wedge$
$\texttt{minAngle} = -30 \wedge$
$\texttt{maxAngle} = -90$

then

act1 : $\texttt{Disease\_step6} := \texttt{LVH\_cause}$

end

Event *RVH_Assessment* $\widehat{=}$
RVH Assessment

extends *RVH_Assessment*

any

age age od men or women
aixs axis for deviation

where

grd1 : $\texttt{P\_Wave\_Peak}(\texttt{II}) \geq 3000$
grd2 : $\texttt{P\_Wave\_Peak}(\texttt{V1}) \geq 3000$
grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$
grd4 : $\texttt{R\_Depth}(\texttt{V1}) \geq 7000 \wedge \texttt{age} > 30$
1 assessment
grd5 : $\texttt{S\_Depth}(\texttt{V5}) \geq 7000 \vee$
$\texttt{S\_Depth}(\texttt{V6}) \geq 7000$
2 assessment

grd6 : $\texttt{R\_S\_Ratio(V1)} \geq 100$

R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment

grd7 : $\texttt{R\_S\_Ratio(V5)} \leq 100$
$\vee$
$\texttt{R\_S\_Ratio(V6)} \leq 100$

4 assessment

grd8 : $\texttt{aixs} \in 0\,..\,360 \wedge \texttt{aixs} \geq 110$

5 assessment

grd9 : $\texttt{Disease\_step2} \notin \{\texttt{LBBB}, \texttt{RBBB}\}$

grd10 : $\texttt{QRS\_Int} < 120$

grd11 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

$AorB : fromstep8development$
$\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd12grd13 : $\texttt{Asy\_T\_Inversion\_strain(V1)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V2)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V3)} = \texttt{TRUE}$

grd14 : $\texttt{Heart\_State} = \texttt{KO}$

grd15 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

grd16 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge$
$\texttt{minAngle} = 110 \wedge$
$\texttt{maxAngle} = 180$

then

act1 : $\texttt{Disease\_step6} := \texttt{RVH}$

end

Event *T_Wave_Assessment_Peaked_V123456* $\widehat{=}$

T Wave Assessment

extends *T_Wave_Assessment_Peaked_V123456*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{V1}, \texttt{V2}, \texttt{V3}, \texttt{V4}, \texttt{V5}, \texttt{V6}\} \Rightarrow \texttt{T\_Wave\_State(l)} = \texttt{Peaked}$

grd2 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step8} := \texttt{Hyperkalemia}$

end

Event *T_Wave_Assessment_Peaked_V12* $\widehat{=}$

extends *T_Wave_Assessment_Peaked_V12*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\mathtt{T\_Wave\_State(V1) = Peaked} \land$
$\mathtt{T\_Wave\_State(V2) = Peaked}$

grd3 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd4 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion(l)} < 5000$
step 8 B

grd5 : $\mathtt{T\_Normal\_Status = FALSE}$

grd6 : $\lor$
$(\text{Axis\_Devi} = \text{RAD} \land$
$minAngle = 110 \land$
$maxAngle = 180)$

then

act1 : $\mathtt{Mice\_State := normal\_variant}$

end

Event *T_Wave_Assessment_Peaked_V12_MI* $\widehat{=}$
posterior MI using T wave assessment in LEADS V1 and V2

extends *T_Wave_Assessment_Peaked_V12_MI*

when

grd1 : $\mathtt{T\_Wave\_State(V1) = Peaked} \land$
$\mathtt{T\_Wave\_State(V2) = Peaked}$

grd6 : $\mathtt{Heart\_State = KO}$

grd2 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd3 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion(l)} > 5000$

grd4 : $\mathtt{T\_inversion\_l\_d(V2) = Localized} \land$
$\mathtt{T\_inversion\_l\_d(V3) = Localized} \land$
$\mathtt{T\_inversion\_l\_d(V4) = Localized} \land$
$\mathtt{T\_inversion\_l\_d(V5) = Localized}$

grd5 : $\mathtt{T\_inversion\_l\_d(II) = Localized} \land$
$\mathtt{T\_inversion\_l\_d(III) = Localized} \land$
$\mathtt{T\_inversion\_l\_d(aVF) = Localized}$

grd7 : $\mathtt{T\_Normal\_Status = FALSE}$

then

act1 : $\mathtt{Disease\_step8 := posterior\_MI}$

end

Event *T_Wave_Assessment_Flat* $\widehat{=}$

extends *T_Wave_Assessment_Flat*

when

$\text{grd1}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Flat}$

$\text{grd4}: \text{Heart\_State} = \text{KO}$

$\text{grd2}: \quad \vee$

$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

step 8 B

$\text{grd3}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) < 5000$

$\text{grd5}: \text{T\_Normal\_Status} = \text{FALSE}$

then

$\text{act1}: \text{Disease\_step8} := \text{Nonspecific\_ST\_T\_changes}$

$\text{act2}: \text{Disease\_step8\_B} :\in \{\text{Cardiomyopathy}, \text{Electrolyte\_depletion}, \text{Alcohol}, \text{Myocarditis}, \text{Other}\}$

end

Event *T_Wave_Assessment_Inverted_Yes* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_Yes*

when

$\text{grd1}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$

$\text{grd2}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{TRUE}$
$\vee$
$\text{Q\_Normal\_Status} = \text{FALSE}$

$\text{grd3}: \text{Heart\_State} = \text{KO}$

then

$\text{act1}: \text{Disease\_step8} :\in \{\text{Definite\_ischemia}, \text{Probable\_ischemia}, \text{Digitalis\_effect}\}$

end

Event *T_Wave_Assessment_Inverted_No* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_No*

when

$\text{grd1}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$

$\text{grd2}: \forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{FALSE}$
$\vee$
$\text{Q\_Normal\_Status} = \text{TRUE}$

$\text{grd3}: \text{Heart\_State} = \text{KO}$

then

$\text{act1}: \text{Disease\_step8} := \text{Nonspecific}$

end

Event *T_Wave_Assessment_Inverted_Yes_PM* $\widehat{=}$

PM - pulmonary embolism this disease is already defined in previous development.

extends *T_Wave_Assessment_Inverted_Yes_PM*

when

$\text{grd1}: \text{P\_Wave\_Peak}(\text{II}) \geq 3000$

$\text{grd2}: \text{P\_Wave\_Peak}(\text{V1}) \geq 3000$

$\text{grd3}: \text{Disease\_step6} = \text{RAE}$

grd4 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

$A : step8$
$\neg(\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$
$((ST\_seg\_ele(l) \geq 1000 \wedge ST\_seg\_ele(k) \geq 1000) \vee$
$(ST\_elevation(l) = TRUE \wedge ST\_elevation(k) = TRUE)$
$\vee$
$(Abnormal\_Shaped\_ST(l) = TRUE \wedge Abnormal\_Shaped\_ST(k) = TRUE))$
$\Rightarrow$
$l \neq k))$

grd5grd6 : $\texttt{Asy\_T\_Inversion\_strain(V1)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V2)} = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain(V3)} = \texttt{TRUE}$

grd7 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge$
$\texttt{minAngle} = 110 \wedge$
$\texttt{maxAngle} = 180$

grd8 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd9 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{pulmonary\_embolism}$

end

Event *T_Wave_Assessment_B* $\widehat{=}$
B for alternate method of T wave assessment

extends *T_Wave_Assessment_B*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{I}, \texttt{II}, \texttt{V3}, \texttt{V4}, \texttt{V5}, \texttt{V6}\} \Rightarrow \texttt{T\_Wave\_State\_B(l)} = \texttt{Upright}$

grd2 : $\texttt{T\_Wave\_State\_B(aVL)} = \texttt{Inverted\_B}$

grd3 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{III}, \texttt{aVL}, \texttt{aVF}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{T\_Wave\_State\_B(l)} = \texttt{Variable}$

then

act1 : $\texttt{T\_Normal\_Status} := \texttt{TRUE}$

end

Event *T_Wave_Assessment_B_DI* $\widehat{=}$
abnormal T wave .....in B ...DI(Definite Ischemia)

extends *T_Wave_Assessment_B_DI*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State(l)} = \texttt{Inverted}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation(l)} = \texttt{TRUE}$
$\vee$
$\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

grd3 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$
added in step-8 B

grd5 : $\texttt{Heart\_State} = \texttt{KO}$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$((\texttt{ST\_seg\_ele(l)} \geq 1000 \wedge \texttt{ST\_seg\_ele(k)} \geq 1000) \vee$
$(\texttt{ST\_elevation(l)} = \texttt{TRUE} \wedge \texttt{ST\_elevation(k)} = \texttt{TRUE})$
$\vee$
$(\texttt{Abnormal\_Shaped\_ST(l)} = \texttt{TRUE} \wedge \texttt{Abnormal\_Shaped\_ST(k)} = \texttt{TRUE}))$

$\wedge$
$l \neq k$
added in step-8 B

then

act1 : $Disease\_step8 := Definite\_ischemia$

end

Event *T_Inversion_Likely_Ischemia* $\widehat{=}$
probable Ischemia or Likly ischemia

extends *T_Inversion_Likely_Ischemia*

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$
grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE$
grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$
1 mm= 1000
grd4 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$
grd5 : $T\_inversion\_l\_d(V2) = Localized \wedge$
$T\_inversion\_l\_d(V3) = Localized \wedge$
$T\_inversion\_l\_d(V4) = Localized \wedge$
$T\_inversion\_l\_d(V5) = Localized$
grd6 : $T\_inversion\_l\_d(II) = Localized \wedge$
$T\_inversion\_l\_d(III) = Localized \wedge$
$T\_inversion\_l\_d(aVF) = Localized$
b. of Deep inversion ¿ 5mm
grd7 : $Heart\_State = KO$
grd8 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8 := Probable\_ischemia$

end

Event *T_Inversion_Diffuse_B* $\widehat{=}$
Step 8 B for c.

extends *T_Inversion_Diffuse_B*

when

grd1 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$
grd2 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$

$grd3: \forall l \cdot l \in LEADS \Rightarrow T\_inversion\_l\_d(l) = Diffuse$
$grd4: Heart\_State = KO$
$grd5: T\_Normal\_Status = FALSE$

then

$act1: Disease\_step8\_B :\in \{Cardiomyopathy, other\_nonspecific\}$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_less_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_less_40*

any

age

where

$grd1: QRS\_Axis\_State(I) = D\_Upright \wedge QRS\_Axis\_State(aVF) = D\_Upright$
$grd2: age \in \mathbb{N} \wedge age < 40$

then

$act1: minAngle := 0$
$act2: maxAngle := 110$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_gre_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_gre_40*

any

age

where

$grd1: QRS\_Axis\_State(I) = D\_Upright \wedge QRS\_Axis\_State(aVF) = D\_Upright$
$grd2: age \in \mathbb{N} \wedge age > 40$

then

$act1: minAngle := -30$
$act2: maxAngle := 90$

end

Event *Axis_Assessment_QRS_upright_No_QRS_positive* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_positive*

when

$grd1: \neg(QRS\_Axis\_State(I) = D\_Upright \wedge QRS\_Axis\_State(aVF) = D\_Upright)$
$grd2: QRS\_Axis\_State(I) = D\_Positive \wedge QRS\_Axis\_State(aVF) = D\_Positive$
$grd3: Heart\_State = KO$

then

$act1: minAngle := -30$
$act2: maxAngle := -90$
$act3: Axis\_Devi := LAD$

end

Event *Axis_Assessment_QRS_upright_No_QRS_negative* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_negative*

when

grd1 : $\neg(\mathtt{QRS\_Axis\_State}(\mathtt{I}) = \mathtt{D\_Upright} \land \mathtt{QRS\_Axis\_State}(\mathtt{aVF}) = \mathtt{D\_Upright})$

grd2 : $\mathtt{QRS\_Axis\_State}(\mathtt{I}) = \mathtt{D\_Negative} \land \mathtt{QRS\_Axis\_State}(\mathtt{aVF}) = \mathtt{D\_Negative}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{minAngle} := 110$

act2 : $\mathtt{maxAngle} := 180$

act3 : $\mathtt{Axis\_Devi} := \mathtt{RAD}$

end

Event *Misc_Disease_Step9_LAD* $\widehat{=}$

extends *Misc_Disease_Step9_LAD*

when

grd1 : $\mathtt{Axis\_Devi} = \mathtt{LAD} \land \mathtt{minAngle} = -30 \land \mathtt{maxAngle} = -90$

grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step9} :\in \{\mathtt{LAFB}, \mathtt{MSCHD}, \mathtt{Some\_Form\_VT}, \mathtt{ED\_OC}\}$

end

Event *Misc_Disease_Step9_RAD* $\widehat{=}$

extends *Misc_Disease_Step9_RAD*

when

grd1 : $\mathtt{Axis\_Devi} = \mathtt{RAD} \land \mathtt{minAngle} = 110 \land \mathtt{maxAngle} = 180$

grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step9} :\in \{\mathtt{LPFB}, \mathtt{NV\_MSEC}\}$

end

Event *R_Q_Assessment_R_Abnormal_V56_axis_deviation* $\widehat{=}$

extends *R_Q_Assessment_R_Abnormal_V56_axis_deviation*

when

grd1 : $\mathtt{Q\_Wave\_State}(\mathtt{V5}) = \mathtt{TRUE} \land \mathtt{Q\_Wave\_State}(\mathtt{V6}) = \mathtt{TRUE}$

grd2 : $\mathtt{Axis\_Devi} = \mathtt{RAD} \land \mathtt{minAngle} = 110 \land \mathtt{maxAngle} = 180$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} := \mathtt{lateral\_MI}$

end

Event *Miscellaneous_Conditions_Step10* $\widehat{=}$

extends *Miscellaneous_Conditions_Step10*

when

grd1 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step10} :\in \{\texttt{Incomplete\_RBBB}, \texttt{Pericarditis}, \texttt{Long\_QT}, \texttt{Hypokalemia}, \texttt{Digitalis\_toxicity}, \texttt{Electrical\_alternans}, \texttt{Electronic\_pacing}, \texttt{Hypothermia}, \texttt{Hypercalcemia}\}$

end

Event *Misc_Disease_Step10_Dextrcardia_Test* $\widehat{=}$

extends *Misc_Disease_Step10_Dextrcardia_Test*

when

grd1 : $\texttt{Axis\_Devi} = \texttt{RAD} \land \texttt{minAngle} = 110 \land \texttt{maxAngle} = 180$

grd2 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step9} := \texttt{Dextrocardia}$

end

Event *Rhythm_test_FALSE_Step11* $\widehat{=}$

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor \texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor \texttt{RR\_Interval}(\texttt{l}) \neq \texttt{PP\_Interval}(\texttt{l})) \lor \texttt{P\_Positive}(\texttt{II}) = \texttt{FALSE}$

grd2 : $\texttt{rate} \in 1 \,..\, 300$

grd5 : $rate \in 1 \,..\, 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

act4 : $Disease\_step11 :\in \{Atrial\_Premature\_Beats, Ventricular\_Premature\_Beats, Nodal\_Premature\_Beats, Bradyarrhythmias, Narrow\_QRS\_Tachycardias, Wide\_QRS\_Tachycardias\}$

end

END

An Event-B Specification of Step11_Abnormal_Rhythm_Ref1
Generated Date: 25 Nov 2010 @ 03:39:53 PM

MACHINE Step11_Abnormal_Rhythm_Ref1

REFINES Step_11_Abnormal_Rhythm

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx, Step11_ctx

VARIABLES

`RR_Int_equidistant` RR Interval
`PP_Int_equidistant` PP Interval
`P_Positive` P wave positive or negative
`Sinus` Sinus Rhythm
`Heart_Rate` Heart Rate in BPM
`Heart_State` OK or KO for heart state after ECG Interpretation
`PR_Int` PR Interval
`Disease_step2` At level 2 Disease Codes
`QRS_Int` QRS Interval
`M_Shape_Complex` M-shaped complex in Leads
`Slurred_S` Slurred S wave in Leads
`Notched_R` Notched R wave in Leads
`Small_R_QS` A small R or QS wave in V1 and V2
`Slurred_S_duration` Slurred S duration
`Delta_Wave` Delta Wave
`Disease_step3`
`ST_elevation` ST segment elevation (Coved or Saddle-back)
`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)
`ST_seg_ele` ST segment for elevation 1mm=0.1mV
`Disease_step4`
`Q_Width` Q wave width
`Q_Depth` Q wave depth
`Q_Normal_Status` Q wave normal or abnormal
`Age_of_Inf` Age of Infarct
`Disease_step5`
`Mice_State`
`R_Depth` R wave depth or height (also use in Step 7)
`R_Normal_Status` R wave normal or abnormal
`Q_Wave_State` Q wave states for all LEADS
`P_Wave_Peak` function to estimate the peak of LEADS signal
`Disease_step6`
`PP_Interval`
`RR_Interval`
`Diphasic`
`P_Wave_Broad`

`S_Depth` S wave depth or height

`R_S_Ratio` R wave and S wave Ratio function

`T_Wave_State` T wave patterns...

`Disease_step8`

`T_Wave_State_B` B for alternative method of T wave assessment

`T_Normal_Status` T wave normal or abnormal

`Abnormal_Shaped_ST`

`Asy_T_Inversion_strain` Asymmetric T wave Inversion strain pattern

`T_inversion` Deep T wave inversion

`T_inversion_l_d` T inversion Localized and Diffuse

`Disease_step8_B`

`QRS_Axis_State` QRS Axis Direction

`minAngle` min. value of angle of Axis in degree

`maxAngle` max. value of angle of Axis in degree

`Axis_Devi` Axis Deviation in LEADS...

`Disease_step9`

`Disease_step10`

`MC_Step10_Test_Needed` Miscellaneous Conditions test in Step 10

`Disease_step11`

`Distease_step11_NW_QRST`

`ST_depression`

INVARIANTS

inv1 : $Distease\_step11\_NW\_QRST \in Disease\_Codes\_Step11\_NW\_QRS\_T$

inv2 : $Sinus = Yes \land Distease\_step11\_NW\_QRST \in \{Ventricular\_Tachycardia, Supraventricular\_Tachycardia, AVNRT, WPW\_Syndrome\_Orthodromic, Sinus\_Tachycardia, Atrial\_Tachycardia, AF\_Fixed\_AV\_Conduction, WPW\_Syndrome\_Antidromic, AF\_BBB\_WPW\_Synd\_Antidromic, AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti, Torsades\_de\_pointes\} \Rightarrow Heart\_State = KO$

inv3 : $Sinus = Yes \land Distease\_step11\_NW\_QRST \in \{Sinus\_Tachycardia, AVNRT, AF\_Fixed\_AV\_Conduction, AT\_Paroxysmal\_NParoxysmal, WPW\_Syndrome\_OCMT, Atrail\_Fibrillation, AF\_Variable\_AV\_Conduction, AT\_Variable\_AV\_Block, Multifocal\_Atrial\_Tachycardia\} \Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $\mathtt{RR\_Int\_equidistant} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act2 : $\mathtt{PP\_Int\_equidistant} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act3 : $\mathtt{P\_Positive} :\in \mathtt{LEADS} \to \mathtt{BOOL}$

act4 : $\mathtt{Sinus} := \mathtt{No}$

act5 : $\mathtt{PP\_Interval} :\in \mathtt{LEADS} \to \mathbb{N}$

act6 : $\mathtt{RR\_Interval} :\in \mathtt{LEADS} \to \mathbb{N}$

act7 : $\mathtt{Heart\_Rate} :\in 1 .. 300$

act8 : $\mathtt{Heart\_State} := \mathtt{KO}$

act9 : $\mathtt{PR\_Int} := 120$

act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → $\mathbb{N}_1$
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → $\mathbb{N}$
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → $\mathbb{N}$
act23 : Q_Width :∈ LEADS → $\mathbb{N}$
act24 : Q_Depth :∈ LEADS → $\mathbb{N}$
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → $\mathbb{N}$
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → $\mathbb{N}$
act34 : P_Wave_Peak :∈ LEADS → $\mathbb{N}$
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → $\mathbb{N}$
act37 : R_S_Ratio :∈ LEADS → $\mathbb{N}$
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → $\mathbb{N}$
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : Disease_step10 := NDS10
act53 : MC_Step10_Test_Needed := FALSE
act54 : Disease_step11 := NDS11
act55 : *Distease_step11_NW_QRST* := *NDS11_NW_QRS*

end

Event *Rhythm_test_TRUE* ≙
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land PP\_Int\_equidistant(l) = TRUE \land$
$RR\_Int\_equidistant(l) = TRUE \land$
$RR\_Interval(l) = PP\_Interval(l))$
$\land$
$P\_Positive(II) = TRUE$

grd4 : $rate \in 60 .. 100$

60..100 is the range of normal heart rate

grd5 : $PR\_Int \leq 200$

Heart is Normal if PR $\leq$ 200 QRS_Int < 120

$HeartisNormalifQRS < 120$

grd6grd7 : $Disease\_step2 = NDS2$

grd8 : $Disease\_step3 = NDS3$

grd9 : $Disease\_step4 = NDS4$

grd10 : $Disease\_step5 = NDS5$

grd11 : $Disease\_step6 = NDS6$

grd12 : $Disease\_step8 = NDS8$

grd13 : $Disease\_step8\_B = NDS8B$

grd14 : $Disease\_step9 = NDS9$

grd15 : $Disease\_step10 = NDS10$

grd16 : $Disease\_step11 = NDS11$

grd17 : $Distease\_step11\_NW\_QRST = NDS11\_NW\_QRS$

then

act1 : $Sinus := Yes$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := OK$

end

Event *Rhythm_test_FALSE* $\widehat{=}$

Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any

rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \lor$
$RR\_Int\_equidistant(l) = FALSE \lor$
$RR\_Interval(l) \neq PP\_Interval(l))$
$\lor$
$P\_Positive(II) = FALSE$

grd2 : $rate \in 1 .. 300$

then

act1 : $Sinus := No$

act2 : $Heart\_Rate := rate$

act3 : $Heart\_State := KO$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \land$ PP_Int_equidistant$(l) =$ TRUE $\land$
RR_Int_equidistant$(l) =$ TRUE $\land$
RR_Interval$(l) =$ PP_Interval$(l))$
$\land$
P_Positive$(II) =$ TRUE

grd5 : rate $\in 1 \mathinner{..} 300 \setminus 60 \mathinner{..} 100$
60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : Disease_step3 = WPW_Syndrome $\lor$ Disease_step3 = Brugada_Syndrome $\lor$
Disease_step3 = RV_Dysplasia $\lor$ Disease_step3 = IVCD

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *PR_Test* $\widehat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : pr $\in 120 \mathinner{..} 220$
time interval in (ms.)

grd2 : pr > 200

grd3 : Sinus = Yes

grd4 : Heart_State = KO

then

act1 : PR_Int := pr

act2 : Disease_step2 := First_degree_AV_Block

end

Event *QRS_Test_LBBB* $\widehat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : qrs $\in 50 \mathinner{..} 150$

grd2 : qrs ≥ 120

grd3 : Sinus = Yes

grd4 : Heart_State = KO

grd5 : $\texttt{Notched\_R(I)} = \texttt{TRUE} \land$
$\texttt{Notched\_R(V5)} = \texttt{TRUE} \land$
$\texttt{Notched\_R(V6)} = \texttt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\texttt{Small\_R\_QS(V1)} = \texttt{TRUE} \land$
$\texttt{Small\_R\_QS(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Q\_Wave\_State(V1)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V2)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V3)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V4)} = \texttt{TRUE}$

from step 5

grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

from step 5

grd9 : $\texttt{Axis\_Devi} = \texttt{LAD} \land$
$\texttt{minAngle} = -30 \land$
$\texttt{maxAngle} = -90$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$

Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex(V1)} = \texttt{TRUE} \land$
$\texttt{M\_Shape\_Complex(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S(I)} = \texttt{TRUE} \land$
$\texttt{Slurred\_S(V5)} = \texttt{TRUE} \land$
$\texttt{Slurred\_S(V6)} = \texttt{TRUE}$

grd8 : $\texttt{Slurred\_S\_duration(I)} > 40 \land$
$\texttt{Slurred\_S\_duration(V5)} > 40 \land$
$\texttt{Slurred\_S\_duration(V6)} > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$

QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt

d_wave

exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \vee \texttt{sympt} = \texttt{A\_LBBB}$

grd3 : $\texttt{d\_wave} \in \mathbb{N}$

grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$

Delta Wave + PR $\leq$ 120 `Heart_State = KO`

grd5grd6 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd7 : $\texttt{exmi} \in \texttt{Mice\_State5} \wedge \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act2 : $\texttt{Delta\_Wave} := \texttt{d\_wave}$

act3 : $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{Slurred\_S}(\texttt{V5}) = \texttt{FALSE} \wedge$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{FALSE}$

grd5 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$

grd6 : $\texttt{ST\_elevation}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{ST\_elevation}(\texttt{V2}) = \texttt{TRUE}$

grd7 : $\texttt{Sinus} = \texttt{Yes}$

then

act1 : $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$

Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt

dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

grd3 : $\texttt{QRS\_Int} \geq 110$

grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$

grd5 : $\texttt{Epsilon\_Wave}(\texttt{V1}) = \texttt{TRUE} \wedge$
$\texttt{Epsilon\_Wave}(\texttt{V3}) = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$

grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$$
$$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$$
$$\wedge$$
$$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$$
$$\wedge\, l1 \neq k1$$
$$\wedge$$
$$($$
$$(l1 = V1 \wedge k1 = V2) \vee$$
$$(l1 = V2 \wedge k1 = V3) \vee$$
$$(l1 = V3 \wedge k1 = V4) \vee$$
$$(l1 = V4 \wedge k1 = V5) \vee$$
$$(l1 = V5 \wedge k1 = V6)$$
$$)$$
$$))$$

grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$
Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression}(\mathtt{l}) \geq 1000 \wedge \mathtt{ST\_depression}(\mathtt{k}) \geq 1000)$
$\wedge \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \in \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$
Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : $\mathtt{Sinus} = \mathtt{Yes}$

grd3 : $\vee$
$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \wedge \mathtt{k} \in \mathtt{LEADS} \wedge$
$(\mathtt{ST\_depression}(\mathtt{l}) \geq 1000 \wedge \mathtt{ST\_depression}(\mathtt{k}) \geq 1000)$
$\wedge \mathtt{l} \neq \mathtt{k}$

grd5 : $\mathtt{Disease\_step4} \notin \{\mathtt{Troponin}, \mathtt{CK\_MB}\}$

grd6 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion}(\mathtt{l}) < 5000$

grd7 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step4} := \mathtt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : $\mathtt{Q\_Width}(\mathtt{II}) < 40 \wedge \mathtt{Q\_Depth}(\mathtt{II}) \leq 3000 \wedge$
$\mathtt{Q\_Width}(\mathtt{aVF}) < 40 \wedge \mathtt{Q\_Depth}(\mathtt{aVF}) \leq 3000 \wedge$
$\mathtt{Q\_Width}(\mathtt{aVL}) < 40$

1000 micrometer= 1 milimeter

grd2 : $\mathtt{Q\_Width}(\mathtt{III}) \leq 40 \wedge \mathtt{Q\_Depth}(\mathtt{III}) \leq 7000 \wedge \mathtt{Q\_Depth}(\mathtt{aVL}) \leq 7000$

grd3 : $\mathtt{Q\_Depth}(\mathtt{I}) < 40 \wedge \mathtt{Q\_Depth}(\mathtt{I}) \leq 1500$

then

act1 : $\mathtt{Q\_Normal\_Status} := \mathtt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(V5) $\geq$ 40 $\wedge$ Q_Depth(V5) $>$ 3000 $\wedge$
Q_Width(V6) $\geq$ 40 $\wedge$ Q_Depth(V6) $>$ 3000

grd5 : Q_Width(aVL) $\geq$ 40 $\wedge$ Q_Depth(aVL) $>$ 7000

grd6 : Q_Depth(I) $\geq$ 40 $\wedge$ Q_Depth(I) $>$ 1500

grd7 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_anterior_MI

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(II) $\geq$ 40 $\wedge$ Q_Depth(II) $>$ 3000 $\wedge$
Q_Width(III) $>$ 40 $\wedge$ Q_Depth(III) $>$ 7000 $\wedge$
Q_Width(aVF) $\geq$ 40 $\wedge$ Q_Depth(aVF) $>$ 3000

grd5 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_inferior_MI

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\mathtt{Disease\_step4} = \mathtt{Acute\_inferior\_MI}$
$\lor$
$\mathtt{Disease\_step5} \in \{\mathtt{anterior\_MI}, \mathtt{LVH}, \mathtt{emphysema}\}$
$\lor$
$\mathtt{Mice\_State} = \mathtt{Exclude\_Mimics\_MI}$
$\lor$
$\mathtt{Disease\_step2} = \mathtt{LBBB}$

then

act1 : $\mathtt{Age\_of\_Inf} :\in \{\mathtt{recent}, \mathtt{old}, \mathtt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\mathtt{Disease\_step4} = \mathtt{Acute\_inferior\_MI}$

grd2 : $\mathtt{exmi} \in \mathtt{Mice\_State5} \land \mathtt{exmi} = \mathtt{Exclude\_Mimics\_MI}$

then

act1 : $\mathtt{Disease\_step5} := \mathtt{Hypertrophic\_cardiomyopathy}$

act2 : $\mathtt{Mice\_State} := \mathtt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\mathtt{R\_Depth(V1)} \geq 0 \land \mathtt{R\_Depth(V1)} \leq 6000 \land \mathtt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\mathtt{R\_Depth(V2)} > 200 \land \mathtt{R\_Depth(V2)} \leq 12000$

grd3 : $\mathtt{R\_Depth(V2)} \geq 1000 \land \mathtt{R\_Depth(V2)} \leq 24000$

then

act1 : $\mathtt{R\_Normal\_Status} := \mathtt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Mice\_State} :\in \{\mathtt{late\_transition}, \mathtt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$
R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{Q\_Wave\_State(V1)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V2)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V3)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V4)} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} :\in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$

act2 : $\texttt{Mice\_State} := \texttt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$
R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\texttt{Q\_Wave\_State(V5)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V6)} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} := \texttt{Hypertrophic\_cardiomyopathy}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $(\texttt{P\_Wave\_Peak(II)} < 3000 \land$
$\texttt{P\_Wave\_Peak(V1)} < 3000)$
$\lor$
$(\texttt{P\_Wave\_Broad(II)} < 110 \land \texttt{P\_Wave\_Broad(V1)} < 110) \lor$
$\texttt{Diphasic(II)} = \texttt{FALSE} \lor$
$\texttt{Diphasic(V1)} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step6} := \texttt{NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{RAE}$

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes_Check_RAE*

when

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{RV\_strain}$

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \land \texttt{P\_Wave\_Broad(V1)} \geq 110) \lor$
$\texttt{Diphasic(II)} = \texttt{TRUE} \lor$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{LAE}$

end

Event *P_Wave_assessment_Broad_Yes_Check_LAE* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes_Check_LAE*

when

grd1 : $(\texttt{P\_Wave\_Broad(II)} \geq 110 \land \texttt{P\_Wave\_Broad(V1)} \geq 110) \lor$
$\texttt{Diphasic(II)} = \texttt{TRUE} \lor$
$\texttt{Diphasic(V1)} = \texttt{TRUE}$

grd2 : $\texttt{Disease\_step6} = \texttt{LAE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} :\in \{\texttt{mitral\_stenosis}, \texttt{mitral\_regurgitation}, \texttt{LV\_failure}, \texttt{dilated\_cardiomyopathy}\}$

end

Event *LVH_Assessment* $\widehat{=}$
LVH Assessment

extends *LVH_Assessment*

any

`LVH_specificity` specificity in percentage
`sensitivity` sensitivity in percentage
`sex`

where

grd1 : $(\mathtt{P\_Wave\_Broad}(\mathtt{II}) \geq 110 \land \mathtt{P\_Wave\_Broad}(\mathtt{V1}) \geq 110) \lor$
$\mathtt{Diphasic}(\mathtt{II}) = \mathtt{TRUE} \lor$
$\mathtt{Diphasic}(\mathtt{V1}) = \mathtt{TRUE}$

grd2 : $\mathtt{Disease\_step6} = \mathtt{LAE}$

grd5 : $\mathtt{sex} \in \{0, 1\}$

o for men and 1 for women

grd3 : $((\mathtt{S\_Depth}(\mathtt{V1}) + \mathtt{R\_Depth}(\mathtt{V5})) > 35000$
$\lor$
$(\mathtt{S\_Depth}(\mathtt{V1}) + \mathtt{R\_Depth}(\mathtt{V6})) > 35000)$

1mm = 1000 micrometer............. 1 assessment

grd4 : $((\mathtt{R\_Depth}(\mathtt{aVL}) + \mathtt{S\_Depth}(\mathtt{V1}) \geq 24000) \land \mathtt{sex} = 0)$
$\lor$
$((\mathtt{R\_Depth}(\mathtt{aVL}) + \mathtt{S\_Depth}(\mathtt{V1}) \geq 18000) \land \mathtt{sex} = 1)$

2 assessment

grd6 : $\mathtt{LVH\_specificity} = 90$
$\land$
$\mathtt{sensitivity} < 40$

1 and 2 assessment

grd7 : $\mathtt{Disease\_step6} = \mathtt{LAE} \Rightarrow \mathtt{LVH\_specificity} < 98$

3 assesssment

grd8 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

A or B : from step 8 development

grd9 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd10 : $\mathtt{Asy\_T\_Inversion\_strain}(\mathtt{V5}) = \mathtt{TRUE} \land$
$\mathtt{Asy\_T\_Inversion\_strain}(\mathtt{V6}) = \mathtt{TRUE} \land$
$\mathtt{Asy\_T\_Inversion\_strain}(\mathtt{V4}) = \mathtt{TRUE}$

grd11 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd12 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

grd13 : $\mathtt{Axis\_Devi} = \mathtt{LAD} \land$
$\mathtt{minAngle} = -30 \land$
$\mathtt{maxAngle} = -90$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{LVH\_cause}$

end

Event *RVH_Assessment* $\widehat{=}$

RVH Assessment

extends *RVH_Assessment*

any

age age od men or women

aixs axis for deviation

where

grd1 : $\mathtt{P\_Wave\_Peak}(\mathtt{II}) \geq 3000$

$\texttt{grd2}: \texttt{P\_Wave\_Peak(V1)} \geq 3000$
$\texttt{grd3}: \texttt{Disease\_step6} = \texttt{RAE}$
$\texttt{grd4}: \texttt{R\_Depth(V1)} \geq 7000 \land \texttt{age} > 30$
1 assessment
$\texttt{grd5}: \texttt{S\_Depth(V5)} \geq 7000 \lor \texttt{S\_Depth(V6)} \geq 7000$
2 assessment
$\texttt{grd6}: \texttt{R\_S\_Ratio(V1)} \geq 100$
R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
$\texttt{grd7}: \texttt{R\_S\_Ratio(V5)} \leq 100 \lor \texttt{R\_S\_Ratio(V6)} \leq 100$
4 assessment
$\texttt{grd8}: \texttt{aixs} \in 0 \,..\, 360 \land \texttt{aixs} \geq 110$
5 assessment
$\texttt{grd9}: \texttt{Disease\_step2} \notin \{\texttt{LBBB}, \texttt{RBBB}\}$
$\texttt{grd10}: \texttt{QRS\_Int} < 120$
$\texttt{grd11}: (\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE \lor Q\_Normal\_Status = FALSE))$

$AorB : fromstep8development \lor (\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land ((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE) \lor ((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000) \land (Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE))) \Rightarrow l1 \neq k1))$

$\texttt{grd12grd13}: \texttt{Asy\_T\_Inversion\_strain(V1)} = \texttt{TRUE} \land \texttt{Asy\_T\_Inversion\_strain(V2)} = \texttt{TRUE} \land \texttt{Asy\_T\_Inversion\_strain(V3)} = \texttt{TRUE}$
$\texttt{grd14}: \texttt{Heart\_State} = \texttt{KO}$
$\texttt{grd15}: \texttt{T\_Normal\_Status} = \texttt{FALSE}$
$\texttt{grd16}: \texttt{Axis\_Devi} = \texttt{RAD} \land \texttt{minAngle} = 110 \land \texttt{maxAngle} = 180$

then

$\texttt{act1}: \texttt{Disease\_step6} := \texttt{RVH}$

end

Event $T\_Wave\_Assessment\_Peaked\_V123456 \widehat{=}$
T Wave Assessment

extends $T\_Wave\_Assessment\_Peaked\_V123456$

when

$\texttt{grd1}: \forall \texttt{l} \cdot \texttt{l} \in \{\texttt{V1}, \texttt{V2}, \texttt{V3}, \texttt{V4}, \texttt{V5}, \texttt{V6}\} \Rightarrow \texttt{T\_Wave\_State(l)} = \texttt{Peaked}$
$\texttt{grd2}: \texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$
$\texttt{grd3}: \texttt{Heart\_State} = \texttt{KO}$

then

$\texttt{act1}: \texttt{Disease\_step8} := \texttt{Hyperkalemia}$

end

Event $T\_Wave\_Assessment\_Peaked\_V12 \triangleq$

extends $T\_Wave\_Assessment\_Peaked\_V12$

when

grd1 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

grd2 : $\texttt{T\_Wave\_State(V1)} = \texttt{Peaked} \land$
$\texttt{T\_Wave\_State(V2)} = \texttt{Peaked}$

grd3 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd4 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion(l)} < 5000$

step 8 B

grd5 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

grd6 : $\lor$
$(\text{Axis\_Devi} = \text{RAD} \land$
$minAngle = 110 \land$
$maxAngle = 180)$

then

act1 : $\texttt{Mice\_State} := \texttt{normal\_variant}$

end

Event $T\_Wave\_Assessment\_Peaked\_V12\_MI \triangleq$

posterior MI using T wave assessment in LEADS V1 and V2

extends $T\_Wave\_Assessment\_Peaked\_V12\_MI$

when

grd1 : $\texttt{T\_Wave\_State(V1)} = \texttt{Peaked} \land$
$\texttt{T\_Wave\_State(V2)} = \texttt{Peaked}$

grd6 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd3 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion(l)} > 5000$

grd4 : $\texttt{T\_inversion\_l\_d(V2)} = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d(V3)} = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d(V4)} = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d(V5)} = \texttt{Localized}$

grd5 : $\texttt{T\_inversion\_l\_d(II)} = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d(III)} = \texttt{Localized} \land$
$\texttt{T\_inversion\_l\_d(aVF)} = \texttt{Localized}$

grd7 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step8} := \texttt{posterior\_MI}$

end

Event $T\_Wave\_Assessment\_Flat \mathrel{\widehat{=}}$

extends $T\_Wave\_Assessment\_Flat$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Flat$

grd4 : $Heart\_State = KO$

grd2 : $\lor$

$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$

$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$

$\lor$

$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$

$\land$

$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$

$\Rightarrow l1 \neq k1))$

step 8 B

grd3 : $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$

grd5 : $T\_Normal\_Status = FALSE$

then

act1 : $Disease\_step8 := Nonspecific\_ST\_T\_changes$

act2 : $Disease\_step8\_B :\in \{Cardiomyopathy, Electrolyte\_depletion, Alcohol, Myocarditis, Other\}$

end

Event $T\_Wave\_Assessment\_Inverted\_Yes \mathrel{\widehat{=}}$

extends $T\_Wave\_Assessment\_Inverted\_Yes$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$

grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$

$\lor$

$Q\_Normal\_Status = FALSE$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step8 :\in \{Definite\_ischemia, Probable\_ischemia, Digitalis\_effect\}$

end

Event $T\_Wave\_Assessment\_Inverted\_No \mathrel{\widehat{=}}$

extends $T\_Wave\_Assessment\_Inverted\_No$

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$

grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = FALSE$

$\lor$

$Q\_Normal\_Status = TRUE$

grd3 : $Heart\_State = KO$

then

act1 : $Disease\_step8 := Nonspecific$

end

Event $T\_Wave\_Assessment\_Inverted\_Yes\_PM \mathrel{\widehat{=}}$

PM - pulmonary embolism this disease is already defined in previous development.

extends *T_Wave_Assessment_Inverted_Yes_PM*

when

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$

grd4 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

$A : step8$
$\neg(\exists l, k \cdot l \in LEADS \land k \in LEADS \land$
$((ST\_seg\_ele(l) \geq 1000 \land ST\_seg\_ele(k) \geq 1000) \lor$
$(ST\_elevation(l) = TRUE \land ST\_elevation(k) = TRUE)$
$\lor$
$(Abnormal\_Shaped\_ST(l) = TRUE \land Abnormal\_Shaped\_ST(k) = TRUE))$
$\Rightarrow$
$l \neq k))$

grd5grd6 : $\texttt{Asy\_T\_Inversion\_strain(V1)} = \texttt{TRUE} \land$
$\texttt{Asy\_T\_Inversion\_strain(V2)} = \texttt{TRUE} \land$
$\texttt{Asy\_T\_Inversion\_strain(V3)} = \texttt{TRUE}$

grd7 : $\texttt{Axis\_Devi} = \texttt{RAD} \land$
$\texttt{minAngle} = 110 \land$
$\texttt{maxAngle} = 180$

grd8 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd9 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step6} := \texttt{pulmonary\_embolism}$

end

Event *T_Wave_Assessment_B* $\widehat{=}$
B for alternate method of T wave assessment

extends *T_Wave_Assessment_B*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{I}, \texttt{II}, \texttt{V3}, \texttt{V4}, \texttt{V5}, \texttt{V6}\} \Rightarrow \texttt{T\_Wave\_State\_B(l)} = \texttt{Upright}$

grd2 : $\texttt{T\_Wave\_State\_B(aVL)} = \texttt{Inverted\_B}$

grd3 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{III}, \texttt{aVL}, \texttt{aVF}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{T\_Wave\_State\_B(l)} = \texttt{Variable}$

then

act1 : $\texttt{T\_Normal\_Status} := \texttt{TRUE}$

end

Event *T_Wave_Assessment_B_DI* $\widehat{=}$
abnormal T wave .....in B ...DI(Definite Ischemia)

extends *T_Wave_Assessment_B_DI*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State(l)} = \texttt{Inverted}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation(l)} = \texttt{TRUE}$
$\lor$
$\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

grd3 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$
added in step-8 B

grd5 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd4 : $\exists \mathtt{l}, \mathtt{k} \cdot \mathtt{l} \in \mathtt{LEADS} \land \mathtt{k} \in \mathtt{LEADS} \land$
$((\mathtt{ST\_seg\_ele}(\mathtt{l}) \geq 1000 \land \mathtt{ST\_seg\_ele}(\mathtt{k}) \geq 1000) \lor$
$(\mathtt{ST\_elevation}(\mathtt{l}) = \mathtt{TRUE} \land \mathtt{ST\_elevation}(\mathtt{k}) = \mathtt{TRUE})$
$\lor$
$(\mathtt{Abnormal\_Shaped\_ST}(\mathtt{l}) = \mathtt{TRUE} \land \mathtt{Abnormal\_Shaped\_ST}(\mathtt{k}) = \mathtt{TRUE}))$
$\land$
$\mathtt{l} \neq \mathtt{k}$

added in step-8 B

then

act1 : $\mathtt{Disease\_step8} := \mathtt{Definite\_ischemia}$

end

Event *T_Inversion_Likely_Ischemia* $\widehat{=}$
probable Ischemia or Likly ischemia

extends *T_Inversion_Likely_Ischemia*

when

grd1 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State}(\mathtt{l}) = \mathtt{Inverted}$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation}(\mathtt{l}) = \mathtt{TRUE}$
$\lor$
$\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

grd3 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion}(\mathtt{l}) > 5000$

1 mm= 1000

grd4 : $\lor$
$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd5 : $\mathtt{T\_inversion\_l\_d}(\mathtt{V2}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V3}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V4}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{V5}) = \mathtt{Localized}$

grd6 : $\mathtt{T\_inversion\_l\_d}(\mathtt{II}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{III}) = \mathtt{Localized} \land$
$\mathtt{T\_inversion\_l\_d}(\mathtt{aVF}) = \mathtt{Localized}$

b. of Deep inversion ¿ 5mm

grd7 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd8 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step8} := \mathtt{Probable\_ischemia}$

end

Event *T_Inversion_Diffuse_B* $\widehat{=}$
Step 8 B for c.

extends *T_Inversion_Diffuse_B*

when

grd1 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion(l)} > 5000$

grd3 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion\_l\_d(l)} = \mathtt{Diffuse}$

grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

grd5 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step8\_B} :\in \{\mathtt{Cardiomyopathy}, \mathtt{other\_nonspecific}\}$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_less_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_less_40*

any

age

where

grd1 : $\mathtt{QRS\_Axis\_State(I)} = \mathtt{D\_Upright} \wedge$
$\mathtt{QRS\_Axis\_State(aVF)} = \mathtt{D\_Upright}$

grd2 : $\mathtt{age} \in \mathbb{N} \wedge \mathtt{age} < 40$

then

act1 : $\mathtt{minAngle} := 0$

act2 : $\mathtt{maxAngle} := 110$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_gre_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_gre_40*

any

age

where

grd1 : $\mathtt{QRS\_Axis\_State(I)} = \mathtt{D\_Upright} \wedge$
$\mathtt{QRS\_Axis\_State(aVF)} = \mathtt{D\_Upright}$

grd2 : $\mathtt{age} \in \mathbb{N} \wedge \mathtt{age} > 40$

then

act1 : $\mathtt{minAngle} := -30$

act2 : $\mathtt{maxAngle} := 90$

end

Event *Axis_Assessment_QRS_upright_No_QRS_positive* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_positive*

when

grd1 : $\neg(\mathtt{QRS\_Axis\_State(I)} = \mathtt{D\_Upright} \wedge$
$\mathtt{QRS\_Axis\_State(aVF)} = \mathtt{D\_Upright})$

grd2 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Positive} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Positive}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{minAngle} := -30$

act2 : $\texttt{maxAngle} := -90$

act3 : $\texttt{Axis\_Devi} := \texttt{LAD}$

end

Event *Axis_Assessment_QRS_upright_No_QRS_negative* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_negative*

when

grd1 : $\neg(\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Upright} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Upright})$

grd2 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Negative} \land$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Negative}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{minAngle} := 110$

act2 : $\texttt{maxAngle} := 180$

act3 : $\texttt{Axis\_Devi} := \texttt{RAD}$

end

Event *Misc_Disease_Step9_LAD* $\widehat{=}$

extends *Misc_Disease_Step9_LAD*

when

grd1 : $\texttt{Axis\_Devi} = \texttt{LAD} \land$
$\texttt{minAngle} = -30 \land$
$\texttt{maxAngle} = -90$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step9} :\in \{\texttt{LAFB}, \texttt{MSCHD}, \texttt{Some\_Form\_VT}, \texttt{ED\_OC}\}$

end

Event *Misc_Disease_Step9_RAD* $\widehat{=}$

extends *Misc_Disease_Step9_RAD*

when

grd1 : $\texttt{Axis\_Devi} = \texttt{RAD} \land$
$\texttt{minAngle} = 110 \land$
$\texttt{maxAngle} = 180$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step9} :\in \{\texttt{LPFB}, \texttt{NV\_MSEC}\}$

end

Event *R_Q_Assessment_R_Abnormal_V56_axis_deviation* $\widehat{=}$

extends *R_Q_Assessment_R_Abnormal_V56_axis_deviation*

when

grd1 : $\texttt{Q\_Wave\_State}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State}(\texttt{V6}) = \texttt{TRUE}$

grd2 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge$
$\texttt{minAngle} = 110 \wedge$
$\texttt{maxAngle} = 180$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} := \texttt{lateral\_MI}$

end

Event *Miscellaneous_Conditions_Step10* $\widehat{=}$

extends *Miscellaneous_Conditions_Step10*

when

grd1 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step10} :\in \{\texttt{Incomplete\_RBBB}, \texttt{Pericarditis}, \texttt{Long\_QT}, \texttt{Hypokalemia},$
$\texttt{Digitalis\_toxicity}, \texttt{Electrical\_alternans}, \texttt{Electronic\_pacing}, \texttt{Hypothermia}, \texttt{Hypercalcemia}\}$

end

Event *Misc_Disease_Step10_Dextrcardia_Test* $\widehat{=}$

extends *Misc_Disease_Step10_Dextrcardia_Test*

when

grd1 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge$
$\texttt{minAngle} = 110 \wedge$
$\texttt{maxAngle} = 180$

grd2 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step9} := \texttt{Dextrocardia}$

end

Event *Rhythm_test_FALSE_Step11* $\widehat{=}$

extends *Rhythm_test_FALSE_Step11*

any

rate

where

grd1 : $(\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \vee$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \vee$
$\texttt{RR\_Interval}(\texttt{l}) \neq \texttt{PP\_Interval}(\texttt{l}))$
$\vee$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{FALSE}$

grd2 : $\texttt{rate} \in 1 \,..\, 300$

grd5 : $\texttt{rate} \in 1 \,..\, 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : Heart_State := KO

act4 : Disease_step11 :∈ {Atrial_Premature_Beats, Ventricular_Premature_Beats, Nodal_Premature_Beats, Bradyarrhythmias, Narrow_QRS_Tachycardias, Wide_QRS_Tachycardias}

end

Event *Step11_N_QRS_Tachycardia* $\widehat{=}$

Narrow QRS achycardia Regular....

when

grd1 : $Sinus = No$

grd2 : $Heart\_State = KO$

grd3 : $Heart\_Rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$

grd4 : $Disease\_step11 = Narrow\_QRS\_Tachycardias$

then

act1 : $Distease\_step11\_NW\_QRST :\in \{Sinus\_Tachycardia, AVNRT, AF\_Fixed\_AV\_Conduction, AT\_Paroxysmal\_NParoxysmal, WPW\_Syndrome\_OCMT, Atrail\_Fibrillation, AF\_Variable\_AV\_Conduction, AT\_Variable\_AV\_Block, Multifocal\_Atrial\_Tachycardia\}$

end

Event *Step11_W_QRS_Tachycardia* $\widehat{=}$

Wide QRS achycardia Regular....

when

grd1 : $Sinus = No$

grd2 : $Heart\_State = KO$

grd3 : $Heart\_Rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$

grd4 : $Disease\_step11 = Wide\_QRS\_Tachycardias$

then

act1 : $Distease\_step11\_NW\_QRST :\in \{Ventricular\_Tachycardia, Supraventricular\_Tachycardia, AVNRT, WPW\_Syndrome\_Orthodromic, Sinus\_Tachycardia, Atrial\_Tachycardia, AF\_Fixed\_AV\_Conduction, WPW\_Syndrome\_Antidromic, AF\_BBB\_WPW\_Synd\_Antidromic, AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti, Torsades\_de\_pointes\}$

end

END

An Event-B Specification of Step11_Abnormal_Rhythm_Ref2
Generated Date: 25 Nov 2010 @ 03:39:56 PM

MACHINE Step11_Abnormal_Rhythm_Ref2

REFINES Step11_Abnormal_Rhythm_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx, Step11_ctx

VARIABLES

`RR_Int_equidistant` RR Interval

`PP_Int_equidistant` PP Interval

`P_Positive` P wave positive or negative

`Sinus` Sinus Rhythm

`Heart_Rate` Heart Rate in BPM

`Heart_State` OK or KO for heart state after ECG Interpretation

`PR_Int` PR Interval

`Disease_step2` At level 2 Disease Codes

`QRS_Int` QRS Interval

`M_Shape_Complex` M-shaped complex in Leads

`Slurred_S` Slurred S wave in Leads

`Notched_R` Notched R wave in Leads

`Small_R_QS` A small R or QS wave in V1 and V2

`Slurred_S_duration` Slurred S duration

`Delta_Wave` Delta Wave

`Disease_step3`

`ST_elevation` ST segment elevation (Coved or Saddle-back)

`Epsilon_Wave` Epsilon Wave or (a terminal notch in the QRS)

`ST_seg_ele` ST segment for elevation 1mm=0.1mV

`Disease_step4`

`Q_Width` Q wave width

`Q_Depth` Q wave depth

`Q_Normal_Status` Q wave normal or abnormal

`Age_of_Inf` Age of Infarct

`Disease_step5`

`Mice_State`

`R_Depth` R wave depth or height (also use in Step 7)

`R_Normal_Status` R wave normal or abnormal

`Q_Wave_State` Q wave states for all LEADS

`P_Wave_Peak` function to estimate the peak of LEADS signal

`Disease_step6`

`PP_Interval`

`RR_Interval`

`Diphasic`

`P_Wave_Broad`

`S_Depth` S wave depth or height

`R_S_Ratio` R wave and S wave Ratio function

`T_Wave_State` T wave patterns...

`Disease_step8`

`T_Wave_State_B` B for alternative method of T wave assessment

`T_Normal_Status` T wave normal or abnormal

`Abnormal_Shaped_ST`

`Asy_T_Inversion_strain` Asymmetric T wave Inversion strain pattern

`T_inversion` Deep T wave inversion

`T_inversion_l_d` T inversion Localized and Diffuse

`Disease_step8_B`

`QRS_Axis_State` QRS Axis Direction

`minAngle` min. value of angle of Axis in degree

`maxAngle` max. value of angle of Axis in degree

`Axis_Devi` Axis Deviation in LEADS...

`Disease_step9`

`Disease_step10`

`MC_Step10_Test_Needed` Miscellaneous Conditions test in Step 10

`Disease_step11`

`Distease_step11_NW_QRST`

`NW_QRS_Tachycardia_RT_State` QRS Tachcardia Regular or Irregular State

`ST_depression`

INVARIANTS

inv1 : $NW\_QRS\_Tachycardia\_RT\_State \in NW\_QRS\_Tachycardia\_RI$

inv2 : $NW\_QRS\_Tachycardia\_RT\_State = Regular \wedge Distease\_step11\_NW\_QRST \in \{Sinus\_Tachycardia, AVNRT, AF\_Fixed\_AV\_Conduction, AT\_Paroxysmal\_NParoxysmal, WPW\_Syndrome\_OCMT\}$
$\Rightarrow Heart\_State = KO$

inv3 : $NW\_QRS\_Tachycardia\_RT\_State = Irregular \wedge Distease\_step11\_NW\_QRST \in \{Atrail\_Fibrillation, AF\_Variable\_AV\_Conduction, AT\_Variable\_AV\_Block, Multifocal\_Atrial\_Tachycardia\}$
$\Rightarrow Heart\_State = KO$

inv4 : $NW\_QRS\_Tachycardia\_RT\_State = Regular \wedge Disease\_step11\_NW\_QRST \in \{Ventricular\_Tachycardia, Supraventricular\_Tachycardia, AVNRT, WPW\_Syndrome\_Orthodromic, Sinus\_Tachycardia, Atrial\_Tachycardia, AF\_Fixed\_AV\_Conduction, WPW\_Syndrome\_Antidromic\}$
$\Rightarrow Heart\_State = KO$

inv5 : $NW\_QRS\_Tachycardia\_RT\_State = Irregular \wedge Distease\_step11\_NW\_QRST \in \{AF\_BBB\_WPW\_Synd\_Antidromic, AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti, Torsades\_de\_pointes\}$
$\Rightarrow Heart\_State = KO$

EVENTS

Initialisation

extended

begin

act1 : `RR_Int_equidistant` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act2 : `PP_Int_equidistant` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act3 : `P_Positive` $:\in$ `LEADS` $\rightarrow$ `BOOL`

act4 : Sinus := No
act5 : PP_Interval :∈ LEADS → ℕ
act6 : RR_Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → $\mathbb{N}_1$
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : Disease_step10 := NDS10

act53 : $\texttt{MC\_Step10\_Test\_Needed} := \texttt{FALSE}$
act54 : $\texttt{Disease\_step11} := \texttt{NDS11}$
act55 : $\texttt{Distease\_step11\_NW\_QRST} := \texttt{NDS11\_NW\_QRS}$
act56 : $NW\_QRS\_Tachycardia\_RT\_State :\in NW\_QRS\_Tachycardia\_RI$

end

Event *Rhythm_test_TRUE* $\widehat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any
rate

where
grd1 : $(\exists \texttt{l}\cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land$
$\texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l}))$
$\land$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$
grd4 : $\texttt{rate} \in 60 \mathrel{..} 100$
60..100 is the range of normal heart rate
grd5 : $\texttt{PR\_Int} \leq 200$
Heart is Normal if PR ≤ 200 QRS_Int < 120
$HeartisNormalifQRS < 120$
grd6grd7 : $\texttt{Disease\_step2} = \texttt{NDS2}$
grd8 : $\texttt{Disease\_step3} = \texttt{NDS3}$
grd9 : $\texttt{Disease\_step4} = \texttt{NDS4}$
grd10 : $\texttt{Disease\_step5} = \texttt{NDS5}$
grd11 : $\texttt{Disease\_step6} = \texttt{NDS6}$
grd12 : $\texttt{Disease\_step8} = \texttt{NDS8}$
grd13 : $\texttt{Disease\_step8\_B} = \texttt{NDS8B}$
grd14 : $\texttt{Disease\_step9} = \texttt{NDS9}$
grd15 : $\texttt{Disease\_step10} = \texttt{NDS10}$
grd16 : $\texttt{Disease\_step11} = \texttt{NDS11}$
grd17 : $\texttt{Distease\_step11\_NW\_QRST} = \texttt{NDS11\_NW\_QRS}$

then
act1 : $\texttt{Sinus} := \texttt{Yes}$
act2 : $\texttt{Heart\_Rate} := \texttt{rate}$
act3 : $\texttt{Heart\_State} := \texttt{OK}$

end

Event *Rhythm_test_FALSE* $\widehat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any
rate

where
grd1 : $(\forall \texttt{l}\cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor$
$\texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{FALSE} \lor$
$\texttt{RR\_Interval}(\texttt{l}) \neq \texttt{PP\_Interval}(\texttt{l}))$
$\lor$
$\texttt{P\_Positive}(\texttt{II}) = \texttt{FALSE}$

grd2 : $\texttt{rate} \in 1 \,..\, 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *Rhythm_test_TRUE_Rate* $\widehat{=}$

Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \land \texttt{PP\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Int\_equidistant}(\texttt{l}) = \texttt{TRUE} \land \texttt{RR\_Interval}(\texttt{l}) = \texttt{PP\_Interval}(\texttt{l})) \land \texttt{P\_Positive}(\texttt{II}) = \texttt{TRUE}$

grd5 : $\texttt{rate} \in 1 \,..\, 300 \setminus 60 \,..\, 100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : $\texttt{Disease\_step3} = \texttt{WPW\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{Brugada\_Syndrome} \lor \texttt{Disease\_step3} = \texttt{RV\_Dysplasia} \lor \texttt{Disease\_step3} = \texttt{IVCD}$

then

act1 : $\texttt{Sinus} := \texttt{Yes}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : $\texttt{Heart\_State} := \texttt{KO}$

end

Event *PR_Test* $\widehat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : $\texttt{pr} \in 120 \,..\, 220$

time interval in (ms.)

grd2 : $\texttt{pr} > 200$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{PR\_Int} := \texttt{pr}$

act2 : $\texttt{Disease\_step2} := \texttt{First\_degree\_AV\_Block}$

end

Event *QRS_Test_LBBB* $\widehat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{Notched\_R(I)} = \texttt{TRUE} \land$
$\texttt{Notched\_R(V5)} = \texttt{TRUE} \land$
$\texttt{Notched\_R(V6)} = \texttt{TRUE}$

Right Bundle Branch Block (RBBB)

grd6 : $\texttt{Small\_R\_QS(V1)} = \texttt{TRUE} \land$
$\texttt{Small\_R\_QS(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Q\_Wave\_State(V1)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V2)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V3)} = \texttt{TRUE} \land$
$\texttt{Q\_Wave\_State(V4)} = \texttt{TRUE}$

from step 5

grd8 : $\texttt{R\_Normal\_Status} = \texttt{FALSE}$

from step 5

grd9 : $\texttt{Axis\_Devi} = \texttt{LAD} \land$
$\texttt{minAngle} = -30 \land$
$\texttt{maxAngle} = -90$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{LBBB}$

end

Event *QRS_Test_RBBB* $\widehat{=}$

Right Bundle Branch Block (RBBB)

extends *QRS_Test_RBBB*

any

qrs

where

grd1 : $\texttt{qrs} \in 50 \,..\, 150$

grd2 : $\texttt{qrs} \geq 120$

grd3 : $\texttt{Sinus} = \texttt{Yes}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd5 : $\texttt{M\_Shape\_Complex(V1)} = \texttt{TRUE} \land$
$\texttt{M\_Shape\_Complex(V2)} = \texttt{TRUE}$

grd7 : $\texttt{Slurred\_S(I)} = \texttt{TRUE} \land$
$\texttt{Slurred\_S(V5)} = \texttt{TRUE} \land$
$\texttt{Slurred\_S(V6)} = \texttt{TRUE}$

grd8 : $\texttt{Slurred\_S\_duration(I)} > 40 \land$
$\texttt{Slurred\_S\_duration(V5)} > 40 \land$
$\texttt{Slurred\_S\_duration(V6)} > 40$

then

act1 : $\texttt{QRS\_Int} := \texttt{qrs}$

act2 : $\texttt{Disease\_step2} := \texttt{RBBB}$

end

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\widehat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave
exmi

where

grd1 : $\texttt{QRS\_Int} \geq 110$
grd2 : $\texttt{sympt} = \texttt{A\_RBBB} \lor \texttt{sympt} = \texttt{A\_LBBB}$
grd3 : $\texttt{d\_wave} \in \mathbb{N}$
grd4 : $(\texttt{d\_wave} + \texttt{PR\_Int}) \leq 120$
Delta Wave + PR $\leq$ 120 Heart_State = KO
grdgrd6 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$
grd7 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act2 : $\texttt{Delta\_Wave} := \texttt{d\_wave}$
act3 : $\texttt{Disease\_step3} := \texttt{WPW\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\widehat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$
grd2 : $\texttt{Heart\_State} = \texttt{KO}$
grd3 : $\texttt{QRS\_Int} \geq 110$
grd4 : $\texttt{Slurred\_S}(\texttt{V5}) = \texttt{FALSE} \land$
$\texttt{Slurred\_S}(\texttt{V6}) = \texttt{FALSE}$
grd5 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{NDS3}\}$
grd6 : $\texttt{ST\_elevation}(\texttt{V1}) = \texttt{TRUE} \land$
$\texttt{ST\_elevation}(\texttt{V2}) = \texttt{TRUE}$
grd7 : $\texttt{Sinus} = \texttt{Yes}$

then

act1 : $\texttt{Disease\_step3} := \texttt{Brugada\_Syndrome}$

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\widehat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : $\texttt{sympt} = \texttt{A\_RBBB}$
grd2 : $\texttt{Heart\_State} = \texttt{KO}$
grd3 : $\texttt{QRS\_Int} \geq 110$
grd4 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{NDS3}\}$
grd5 : $\texttt{Epsilon\_Wave(V1)} = \texttt{TRUE} \land$
$\texttt{Epsilon\_Wave(V3)} = \texttt{TRUE}$

then

act1 : $\texttt{Disease\_step3} := \texttt{RV\_Dysplasia}$

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\widehat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : $\texttt{QRS\_Int} \geq 110$
grd2 : $\texttt{dis} \in \texttt{Disease\_Codes\_Step3} \setminus \{\texttt{WPW\_Syndrome}, \texttt{Brugada\_Syndrome}, \texttt{RV\_Dysplasia}, \texttt{NDS3}\}$
grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step3} := \texttt{IVCD}$

end

Event *ST_seg_elevation_YES* $\widehat{=}$
ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$
grd2 : $\texttt{Sinus} = \texttt{Yes}$
grd3 : $\lor$
$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \land k1 \in \{V1, V2, V3, V4, V5, V6\} \land$
$(ST\_elevation(l1) = TRUE \land ST\_elevation(k1) = TRUE)$
$\land$
$(ST\_seg\_ele(l1) \geq 1000 \land ST\_seg\_ele(k1) \geq 1000)$
$\land l1 \neq k1$
$\land$
$($
$(l1 = V1 \land k1 = V2) \lor$
$(l1 = V2 \land k1 = V3) \lor$
$(l1 = V3 \land k1 = V4) \lor$
$(l1 = V4 \land k1 = V5) \lor$
$(l1 = V5 \land k1 = V6)$
$)$
$))$
grd4 : $\texttt{Disease\_step4} \in \{\texttt{Acute\_inferior\_MI}, \texttt{Acute\_anterior\_MI}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{STEMI}$

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\widehat{=}$
Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \in \{\texttt{Troponin}, \texttt{CK\_MB}\}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Non\_STEMI}$

end

Event *ST_seg_elevation_NO_TCKMB_No* $\widehat{=}$
Troponin or CK-MB positive No

extends *ST_seg_elevation_NO_TCKMB_No*

when

grd1 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\texttt{Sinus} = \texttt{Yes}$

grd3 : $\vee$

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$
$(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$

grd4 : $\exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$(\texttt{ST\_depression}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_depression}(\texttt{k}) \geq 1000)$
$\wedge\, \texttt{l} \neq \texttt{k}$

grd5 : $\texttt{Disease\_step4} \notin \{\texttt{Troponin}, \texttt{CK\_MB}\}$

grd6 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) < 5000$

grd7 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step4} := \texttt{Ischemia}$

end

Event *Q_Assessment_Normal* $\widehat{=}$
Q wave assessment normal

extends *Q_Assessment_Normal*

when

grd1 : $\texttt{Q\_Width}(\texttt{II}) < 40 \wedge \texttt{Q\_Depth}(\texttt{II}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVF}) < 40 \wedge \texttt{Q\_Depth}(\texttt{aVF}) \leq 3000 \wedge$
$\texttt{Q\_Width}(\texttt{aVL}) < 40$

1000 micrometer= 1 milimeter

grd2 : $\texttt{Q\_Width}(\texttt{III}) \leq 40 \wedge \texttt{Q\_Depth}(\texttt{III}) \leq 7000 \wedge \texttt{Q\_Depth}(\texttt{aVL}) \leq 7000$

grd3 : $\texttt{Q\_Depth}(\texttt{I}) < 40 \wedge \texttt{Q\_Depth}(\texttt{I}) \leq 1500$

then

act1 : $\texttt{Q\_Normal\_Status} := \texttt{TRUE}$

end

Event *Q_Assessment_Abnormal_AMI* $\widehat{=}$
Q wave assessment abnormal for anterolateral MI (AMI)

extends *Q_Assessment_Abnormal_AMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(V5) $\geq$ 40 $\wedge$ Q_Depth(V5) $>$ 3000 $\wedge$
Q_Width(V6) $\geq$ 40 $\wedge$ Q_Depth(V6) $>$ 3000

grd5 : Q_Width(aVL) $\geq$ 40 $\wedge$ Q_Depth(aVL) $>$ 7000

grd6 : Q_Depth(I) $\geq$ 40 $\wedge$ Q_Depth(I) $>$ 1500

grd7 : Q_Normal_Status = FALSE

then

act1 : Disease_step4 := Acute_anterior_MI

end

Event *Q_Assessment_Abnormal_IMI* $\widehat{=}$
Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : $\vee$

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
$(ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE)$
$\wedge$
$(ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000)$
$\wedge\, l1 \neq k1$
$\wedge$
$($
$(l1 = V1 \wedge k1 = V2) \vee$
$(l1 = V2 \wedge k1 = V3) \vee$
$(l1 = V3 \wedge k1 = V4) \vee$
$(l1 = V4 \wedge k1 = V5) \vee$
$(l1 = V5 \wedge k1 = V6)$
$)$
$))$

grd4 : Q_Width(II) $\geq$ 40 $\wedge$ Q_Depth(II) $>$ 3000 $\wedge$
Q_Width(III) $>$ 40 $\wedge$ Q_Depth(III) $>$ 7000 $\wedge$
Q_Width(aVF) $\geq$ 40 $\wedge$ Q_Depth(aVF) $>$ 3000

grd5 : Q_Normal_Status = FALSE

then

act1 : $\texttt{Disease\_step4} := \texttt{Acute\_inferior\_MI}$

end

Event *Determine_Age_of_Infarct* $\widehat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$
$\lor$
$\texttt{Disease\_step5} \in \{\texttt{anterior\_MI}, \texttt{LVH}, \texttt{emphysema}\}$
$\lor$
$\texttt{Mice\_State} = \texttt{Exclude\_Mimics\_MI}$
$\lor$
$\texttt{Disease\_step2} = \texttt{LBBB}$

then

act1 : $\texttt{Age\_of\_Inf} :\in \{\texttt{recent}, \texttt{old}, \texttt{indeterminate}\}$

end

Event *Exclude_Mimics* $\widehat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : $\texttt{Disease\_step4} = \texttt{Acute\_inferior\_MI}$

grd2 : $\texttt{exmi} \in \texttt{Mice\_State5} \land \texttt{exmi} = \texttt{Exclude\_Mimics\_MI}$

then

act1 : $\texttt{Disease\_step5} := \texttt{Hypertrophic\_cardiomyopathy}$

act2 : $\texttt{Mice\_State} := \texttt{borderline\_Qs}$

end

Event *R_Assessment_Normal* $\widehat{=}$

Q wave assessment normal

extends *R_Assessment_Normal*

any

age

where

grd1 : $\texttt{R\_Depth}(\texttt{V1}) \geq 0 \land \texttt{R\_Depth}(\texttt{V1}) \leq 6000 \land \texttt{age} > 30$

1000 micrometer= 1 milimeter

grd2 : $\texttt{R\_Depth}(\texttt{V2}) > 200 \land \texttt{R\_Depth}(\texttt{V2}) \leq 12000$

grd3 : $\texttt{R\_Depth}(\texttt{V2}) \geq 1000 \land \texttt{R\_Depth}(\texttt{V2}) \leq 24000$

then

act1 : $\texttt{R\_Normal\_Status} := \texttt{TRUE}$

end

Event *R_Assessment_Abnormal* $\widehat{=}$

extends *R_Assessment_Abnormal*

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Mice\_State} :\in \{\mathtt{late\_transition}, \mathtt{normal\_variant}\}$

end

Event *R_Q_Assessment_R_Abnormal_V1234* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : $\mathtt{R\_Normal\_Status} = \mathtt{FALSE}$

grd2 : $\mathtt{Q\_Wave\_State(V1)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V2)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V3)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V4)} = \mathtt{TRUE}$

grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} :\in \{\mathtt{anterior\_MI}, \mathtt{LVH}, \mathtt{emphysema}\}$

act2 : $\mathtt{Mice\_State} := \mathtt{Exclude\_Mimics\_MI}$

end

Event *R_Q_Assessment_R_Abnormal_V56* $\widehat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : $\mathtt{Q\_Wave\_State(V5)} = \mathtt{TRUE} \land$
$\mathtt{Q\_Wave\_State(V6)} = \mathtt{TRUE}$

grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step5} := \mathtt{Hypertrophic\_cardiomyopathy}$

end

Event *P_Wave_assessment_Peaked_Broad_No* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : $(\mathtt{P\_Wave\_Peak(II)} < 3000 \land$
$\mathtt{P\_Wave\_Peak(V1)} < 3000)$
$\lor$
$(\mathtt{P\_Wave\_Broad(II)} < 110 \land \mathtt{P\_Wave\_Broad(V1)} < 110) \lor$
$\mathtt{Diphasic(II)} = \mathtt{FALSE} \lor$
$\mathtt{Diphasic(V1)} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{NDS6}$

end

Event *P_Wave_assessment_Peaked_Yes* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : $\mathtt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\mathtt{P\_Wave\_Peak(V1)} \geq 3000$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RAE}$

end

Event *P_Wave_assessment_Peaked_Yes_Check_RAE* $\widehat{=}$

extends *P_Wave_assessment_Peaked_Yes_Check_RAE*

when

grd1 : $\mathtt{P\_Wave\_Peak(II)} \geq 3000$
grd2 : $\mathtt{P\_Wave\_Peak(V1)} \geq 3000$
grd3 : $\mathtt{Disease\_step6} = \mathtt{RAE}$
grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{RV\_strain}$

end

Event *P_Wave_assessment_Broad_Yes* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : $(\mathtt{P\_Wave\_Broad(II)} \geq 110 \land \mathtt{P\_Wave\_Broad(V1)} \geq 110) \lor$
$\mathtt{Diphasic(II)} = \mathtt{TRUE} \lor$
$\mathtt{Diphasic(V1)} = \mathtt{TRUE}$
grd2 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} := \mathtt{LAE}$

end

Event *P_Wave_assessment_Broad_Yes_Check_LAE* $\widehat{=}$

extends *P_Wave_assessment_Broad_Yes_Check_LAE*

when

grd1 : $(\mathtt{P\_Wave\_Broad(II)} \geq 110 \land \mathtt{P\_Wave\_Broad(V1)} \geq 110) \lor$
$\mathtt{Diphasic(II)} = \mathtt{TRUE} \lor$
$\mathtt{Diphasic(V1)} = \mathtt{TRUE}$
grd2 : $\mathtt{Disease\_step6} = \mathtt{LAE}$
grd3 : $\mathtt{Heart\_State} = \mathtt{KO}$

then

act1 : $\mathtt{Disease\_step6} :\in \{\mathtt{mitral\_stenosis}, \mathtt{mitral\_regurgitation}, \mathtt{LV\_failure}, \mathtt{dilated\_cardiomyopathy}\}$

end

Event *LVH_Assessment* $\widehat{=}$
LVH Assessment

extends *LVH_Assessment*

any

`LVH_specificity` specificity in percentage
`sensitivity` sensitivity in percentage

sex

where

grd1 : $(\texttt{P\_Wave\_Broad}(\texttt{II}) \geq 110 \wedge \texttt{P\_Wave\_Broad}(\texttt{V1}) \geq 110) \vee$
$\texttt{Diphasic}(\texttt{II}) = \texttt{TRUE} \vee$
$\texttt{Diphasic}(\texttt{V1}) = \texttt{TRUE}$

grd2 : $\texttt{Disease\_step6} = \texttt{LAE}$

grd5 : $\texttt{sex} \in \{0, 1\}$

o for men and 1 for women

grd3 : $((\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V5})) > 35000$
$\vee$
$(\texttt{S\_Depth}(\texttt{V1}) + \texttt{R\_Depth}(\texttt{V6})) > 35000)$

1mm = 1000 micrometer............. 1 assessment

grd4 : $((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 24000) \wedge \texttt{sex} = 0)$
$\vee$
$((\texttt{R\_Depth}(\texttt{aVL}) + \texttt{S\_Depth}(\texttt{V1}) \geq 18000) \wedge \texttt{sex} = 1)$

2 assessment

grd6 : $\texttt{LVH\_specificity} = 90$
$\wedge$
$\texttt{sensitivity} < 40$

1 and 2 assessment

grd7 : $\texttt{Disease\_step6} = \texttt{LAE} \Rightarrow \texttt{LVH\_specificity} < 98$

3 assesssment

grd8 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\vee$
$Q\_Normal\_Status = FALSE))$

A or B : from step 8 development

grd9 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd10 : $\texttt{Asy\_T\_Inversion\_strain}(\texttt{V5}) = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain}(\texttt{V6}) = \texttt{TRUE} \wedge$
$\texttt{Asy\_T\_Inversion\_strain}(\texttt{V4}) = \texttt{TRUE}$

grd11 : $\texttt{Heart\_State} = \texttt{KO}$

grd12 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

grd13 : $\texttt{Axis\_Devi} = \texttt{LAD} \wedge$
$\texttt{minAngle} = -30 \wedge$
$\texttt{maxAngle} = -90$

then

act1 : $\texttt{Disease\_step6} := \texttt{LVH\_cause}$

end

Event *RVH_Assessment* $\widehat{=}$

RVH Assessment

extends *RVH_Assessment*

any

age   age od men or women

aixs   axis for deviation

where

grd1 : $\texttt{P\_Wave\_Peak(II)} \geq 3000$

grd2 : $\texttt{P\_Wave\_Peak(V1)} \geq 3000$

grd3 : $\texttt{Disease\_step6} = \texttt{RAE}$

grd4 : $\texttt{R\_Depth(V1)} \geq 7000 \wedge \texttt{age} > 30$

1 assessment

grd5 : $\texttt{S\_Depth(V5)} \geq 7000 \vee \texttt{S\_Depth(V6)} \geq 7000$

2 assessment

grd6 : $\texttt{R\_S\_Ratio(V1)} \geq 100$

R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment

grd7 : $\texttt{R\_S\_Ratio(V5)} \leq 100 \vee \texttt{R\_S\_Ratio(V6)} \leq 100$

4 assessment

grd8 : $\texttt{aixs} \in 0\,..\,360 \wedge \texttt{aixs} \geq 110$

5 assessment

grd9 : $\texttt{Disease\_step2} \notin \{\texttt{LBBB}, \texttt{RBBB}\}$

grd10 : $\texttt{QRS\_Int} < 120$

grd11 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE \vee Q\_Normal\_Status = FALSE))$

$AorB : fromstep8development \vee (\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge ((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE) \vee ((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000) \wedge (Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE))) \Rightarrow l1 \neq k1))$

grd12grd13 : $\texttt{Asy\_T\_Inversion\_strain(V1)} = \texttt{TRUE} \wedge \texttt{Asy\_T\_Inversion\_strain(V2)} = \texttt{TRUE} \wedge \texttt{Asy\_T\_Inversion\_strain(V3)} = \texttt{TRUE}$

grd14 : $\texttt{Heart\_State} = \texttt{KO}$

grd15 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

grd16 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge \texttt{minAngle} = 110 \wedge \texttt{maxAngle} = 180$

then

act1 : $\texttt{Disease\_step6} := \texttt{RVH}$

end

Event $T\_Wave\_Assessment\_Peaked\_V123456 \mathrel{\widehat{=}}$

T Wave Assessment

extends $T\_Wave\_Assessment\_Peaked\_V123456$

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{V1}, \texttt{V2}, \texttt{V3}, \texttt{V4}, \texttt{V5}, \texttt{V6}\} \Rightarrow \texttt{T\_Wave\_State(l)} = \texttt{Peaked}$

grd2 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : Disease_step8 := Hyperkalemia

end

Event *T_Wave_Assessment_Peaked_V12* $\widehat{=}$

extends *T_Wave_Assessment_Peaked_V12*

when

grd1 : R_Normal_Status = FALSE

grd2 : T_Wave_State(V1) = Peaked ∧
T_Wave_State(V2) = Peaked

grd3 : ∨
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd4 : ∀l·l ∈ LEADS ⇒ T_inversion(l) < 5000
step 8 B

grd5 : T_Normal_Status = FALSE

grd6 : ∨
(Axis_Devi = RAD ∧
$minAngle = 110 \wedge$
$maxAngle = 180)$

then

act1 : Mice_State := normal_variant

end

Event *T_Wave_Assessment_Peaked_V12_MI* $\widehat{=}$

posterior MI using T wave assessment in LEADS V1 and V2

extends *T_Wave_Assessment_Peaked_V12_MI*

when

grd1 : T_Wave_State(V1) = Peaked ∧
T_Wave_State(V2) = Peaked

grd6 : Heart_State = KO

grd2 : ∨
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd3 : ∀l·l ∈ LEADS ⇒ T_inversion(l) > 5000

grd4 : T_inversion_l_d(V2) = Localized ∧
T_inversion_l_d(V3) = Localized ∧
T_inversion_l_d(V4) = Localized ∧
T_inversion_l_d(V5) = Localized

grd5 : T_inversion_l_d(II) = Localized ∧
T_inversion_l_d(III) = Localized ∧
T_inversion_l_d(aVF) = Localized

grd7 : T_Normal_Status = FALSE

then

act1 : $\texttt{Disease\_step8} := \texttt{posterior\_MI}$

end

Event *T_Wave_Assessment_Flat* $\widehat{=}$

extends *T_Wave_Assessment_Flat*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Flat}$

grd4 : $\texttt{Heart\_State} = \texttt{KO}$

grd2 : $\lor$

$(\forall l1, k1 \cdot l1 \in LEADS \land k1 \in LEADS \land$
$((ST\_elevation(l1) = FALSE \lor ST\_elevation(k1) = FALSE)$
$\lor$
$((ST\_seg\_ele(l1) < 1000 \lor ST\_seg\_ele(k1) < 1000)$
$\land$
$(Abnormal\_Shaped\_ST(l1) = FALSE \lor Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

step 8 B

grd3 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) < 5000$

grd5 : $\texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

act1 : $\texttt{Disease\_step8} := \texttt{Nonspecific\_ST\_T\_changes}$

act2 : $\texttt{Disease\_step8\_B} :\in \{\texttt{Cardiomyopathy}, \texttt{Electrolyte\_depletion}, \texttt{Alcohol}, \texttt{Myocarditis}, \texttt{Other}\}$

end

Event *T_Wave_Assessment_Inverted_Yes* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_Yes*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Inverted}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation}(\texttt{l}) = \texttt{TRUE}$
$\lor$
$\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step8} :\in \{\texttt{Definite\_ischemia}, \texttt{Probable\_ischemia}, \texttt{Digitalis\_effect}\}$

end

Event *T_Wave_Assessment_Inverted_No* $\widehat{=}$

extends *T_Wave_Assessment_Inverted_No*

when

grd1 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Inverted}$

grd2 : $\forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation}(\texttt{l}) = \texttt{FALSE}$
$\lor$
$\texttt{Q\_Normal\_Status} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step8} := \texttt{Nonspecific}$

end

Event $T\_Wave\_Assessment\_Inverted\_Yes\_PM \widehat{=}$
PM - pulmonary embolism this disease is already defined in previous development.

refines $T\_Wave\_Assessment\_Inverted\_Yes\_PM$

when

grd1 : $P\_Wave\_Peak(II) \geq 3000$
grd2 : $P\_Wave\_Peak(V1) \geq 3000$
grd3 : $Disease\_step6 = RAE$
grd4 : $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$
$\lor$
$Q\_Normal\_Status = FALSE))$

$A : step8$
$\neg(\exists l, k \cdot l \in LEADS \land k \in LEADS \land$
$((ST\_seg\_ele(l) \geq 1000 \land ST\_seg\_ele(k) \geq 1000) \lor$
$(ST\_elevation(l) = TRUE \land ST\_elevation(k) = TRUE)$
$\lor$
$(Abnormal\_Shaped\_ST(l) = TRUE \land Abnormal\_Shaped\_ST(k) = TRUE))$
$\Rightarrow$
$l \neq k))$

grd5grd6 : $Asy\_T\_Inversion\_strain(V1) = TRUE \land$
$Asy\_T\_Inversion\_strain(V2) = TRUE \land$
$Asy\_T\_Inversion\_strain(V3) = TRUE$
grd7 : $Axis\_Devi = RAD \land$
$minAngle = 110 \land$
$maxAngle = 180$
grd8 : $MC\_Step10\_Test\_Needed = TRUE$
grd9 : $Heart\_State = KO$

then

act1 : $Disease\_step6 := pulmonary\_embolism$

end

Event $T\_Wave\_Assessment\_B \widehat{=}$
B for alternate method of T wave assessment

extends $T\_Wave\_Assessment\_B$

when

grd1 : $\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{I}, \mathtt{II}, \mathtt{V3}, \mathtt{V4}, \mathtt{V5}, \mathtt{V6}\} \Rightarrow \mathtt{T\_Wave\_State\_B(l)} = \mathtt{Upright}$
grd2 : $\mathtt{T\_Wave\_State\_B(aVL)} = \mathtt{Inverted\_B}$
grd3 : $\forall \mathtt{l} \cdot \mathtt{l} \in \{\mathtt{III}, \mathtt{aVL}, \mathtt{aVF}, \mathtt{V1}, \mathtt{V2}\} \Rightarrow \mathtt{T\_Wave\_State\_B(l)} = \mathtt{Variable}$

then

act1 : $\mathtt{T\_Normal\_Status} := \mathtt{TRUE}$

end

Event $T\_Wave\_Assessment\_B\_DI \widehat{=}$
abnormal T wave .....in B ...DI(Definite Ischemia)

extends $T\_Wave\_Assessment\_B\_DI$

when

grd1 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_Wave\_State(l)} = \mathtt{Inverted}$
grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{ST\_elevation(l)} = \mathtt{TRUE}$
$\lor$
$\mathtt{Q\_Normal\_Status} = \mathtt{FALSE}$

$\texttt{grd3}: \texttt{T\_Normal\_Status} = \texttt{FALSE}$

added in step-8 B

$\texttt{grd5}: \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd4}: \exists \texttt{l}, \texttt{k} \cdot \texttt{l} \in \texttt{LEADS} \wedge \texttt{k} \in \texttt{LEADS} \wedge$
$((\texttt{ST\_seg\_ele}(\texttt{l}) \geq 1000 \wedge \texttt{ST\_seg\_ele}(\texttt{k}) \geq 1000) \vee$
$(\texttt{ST\_elevation}(\texttt{l}) = \texttt{TRUE} \wedge \texttt{ST\_elevation}(\texttt{k}) = \texttt{TRUE})$
$\vee$
$(\texttt{Abnormal\_Shaped\_ST}(\texttt{l}) = \texttt{TRUE} \wedge \texttt{Abnormal\_Shaped\_ST}(\texttt{k}) = \texttt{TRUE}))$
$\wedge$
$\texttt{l} \neq \texttt{k}$

added in step-8 B

then

$\texttt{act1}: \texttt{Disease\_step8} := \texttt{Definite\_ischemia}$

end

Event *T_Inversion_Likely_Ischemia* $\widehat{=}$

probable Ischemia or Likly ischemia

extends *T_Inversion_Likely_Ischemia*

when

$\texttt{grd1}: \forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_Wave\_State}(\texttt{l}) = \texttt{Inverted}$

$\texttt{grd2}: \forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{ST\_elevation}(\texttt{l}) = \texttt{TRUE}$
$\vee$
$\texttt{Q\_Normal\_Status} = \texttt{FALSE}$

$\texttt{grd3}: \forall \texttt{l} \cdot \texttt{l} \in \texttt{LEADS} \Rightarrow \texttt{T\_inversion}(\texttt{l}) > 5000$

1 mm= 1000

$\texttt{grd4}: \vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

$\texttt{grd5}: \texttt{T\_inversion\_l\_d}(\texttt{V2}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{V3}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{V4}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{V5}) = \texttt{Localized}$

$\texttt{grd6}: \texttt{T\_inversion\_l\_d}(\texttt{II}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{III}) = \texttt{Localized} \wedge$
$\texttt{T\_inversion\_l\_d}(\texttt{aVF}) = \texttt{Localized}$

b. of Deep inversion ¿ 5mm

$\texttt{grd7}: \texttt{Heart\_State} = \texttt{KO}$

$\texttt{grd8}: \texttt{T\_Normal\_Status} = \texttt{FALSE}$

then

$\texttt{act1}: \texttt{Disease\_step8} := \texttt{Probable\_ischemia}$

end

Event *T_Inversion_Diffuse_B* $\widehat{=}$

Step 8 B for c.

extends *T_Inversion_Diffuse_B*

when

grd1 : $\vee$
$(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$
$((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$
$\vee$
$((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$
$\wedge$
$(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$
$\Rightarrow l1 \neq k1))$

grd2 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion(l)} > 5000$
grd3 : $\forall \mathtt{l} \cdot \mathtt{l} \in \mathtt{LEADS} \Rightarrow \mathtt{T\_inversion\_l\_d(l)} = \mathtt{Diffuse}$
grd4 : $\mathtt{Heart\_State} = \mathtt{KO}$
grd5 : $\mathtt{T\_Normal\_Status} = \mathtt{FALSE}$

then

act1 : $\mathtt{Disease\_step8\_B} :\in \{\mathtt{Cardiomyopathy}, \mathtt{other\_nonspecific}\}$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_less_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_less_40*

any

age

where

grd1 : $\mathtt{QRS\_Axis\_State(I)} = \mathtt{D\_Upright} \wedge$
$\mathtt{QRS\_Axis\_State(aVF)} = \mathtt{D\_Upright}$
grd2 : $\mathtt{age} \in \mathbb{N} \wedge \mathtt{age} < 40$

then

act1 : $\mathtt{minAngle} := 0$
act2 : $\mathtt{maxAngle} := 110$

end

Event *Axis_Assessment_QRS_upright_Yes_Age_gre_40* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_Yes_Age_gre_40*

any

age

where

grd1 : $\mathtt{QRS\_Axis\_State(I)} = \mathtt{D\_Upright} \wedge$
$\mathtt{QRS\_Axis\_State(aVF)} = \mathtt{D\_Upright}$
grd2 : $\mathtt{age} \in \mathbb{N} \wedge \mathtt{age} > 40$

then

act1 : $\mathtt{minAngle} := -30$
act2 : $\mathtt{maxAngle} := 90$

end

Event *Axis_Assessment_QRS_upright_No_QRS_positive* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_positive*

when

grd1 : $\neg(\mathtt{QRS\_Axis\_State(I)} = \mathtt{D\_Upright} \wedge$
$\mathtt{QRS\_Axis\_State(aVF)} = \mathtt{D\_Upright})$

grd2 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Positive} \wedge$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Positive}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{minAngle} := -30$

act2 : $\texttt{maxAngle} := -90$

act3 : $\texttt{Axis\_Devi} := \texttt{LAD}$

end

Event *Axis_Assessment_QRS_upright_No_QRS_negative* $\widehat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_negative*

when

grd1 : $\neg(\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Upright} \wedge$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Upright})$

grd2 : $\texttt{QRS\_Axis\_State}(\texttt{I}) = \texttt{D\_Negative} \wedge$
$\texttt{QRS\_Axis\_State}(\texttt{aVF}) = \texttt{D\_Negative}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{minAngle} := 110$

act2 : $\texttt{maxAngle} := 180$

act3 : $\texttt{Axis\_Devi} := \texttt{RAD}$

end

Event *Misc_Disease_Step9_LAD* $\widehat{=}$

extends *Misc_Disease_Step9_LAD*

when

grd1 : $\texttt{Axis\_Devi} = \texttt{LAD} \wedge$
$\texttt{minAngle} = -30 \wedge$
$\texttt{maxAngle} = -90$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step9} :\in \{\texttt{LAFB}, \texttt{MSCHD}, \texttt{Some\_Form\_VT}, \texttt{ED\_OC}\}$

end

Event *Misc_Disease_Step9_RAD* $\widehat{=}$

extends *Misc_Disease_Step9_RAD*

when

grd1 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge$
$\texttt{minAngle} = 110 \wedge$
$\texttt{maxAngle} = 180$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step9} :\in \{\texttt{LPFB}, \texttt{NV\_MSEC}\}$

end

Event *R_Q_Assessment_R_Abnormal_V56_axis_deviation* $\widehat{=}$

extends *R_Q_Assessment_R_Abnormal_V56_axis_deviation*

when

grd1 : $\texttt{Q\_Wave\_State(V5)} = \texttt{TRUE} \wedge$
$\texttt{Q\_Wave\_State(V6)} = \texttt{TRUE}$

grd2 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge$
$\texttt{minAngle} = 110 \wedge$
$\texttt{maxAngle} = 180$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step5} := \texttt{lateral\_MI}$

end

Event *Miscellaneous_Conditions_Step10* $\widehat{=}$

extends *Miscellaneous_Conditions_Step10*

when

grd1 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd2 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step10} :\in \{\texttt{Incomplete\_RBBB}, \texttt{Pericarditis}, \texttt{Long\_QT}, \texttt{Hypokalemia}, \texttt{Digitalis\_toxicity}, \texttt{Electrical\_alternans}, \texttt{Electronic\_pacing}, \texttt{Hypothermia}, \texttt{Hypercalcemia}\}$

end

Event *Misc_Disease_Step10_Dextrcardia_Test* $\widehat{=}$

extends *Misc_Disease_Step10_Dextrcardia_Test*

when

grd1 : $\texttt{Axis\_Devi} = \texttt{RAD} \wedge$
$\texttt{minAngle} = 110 \wedge$
$\texttt{maxAngle} = 180$

grd2 : $\texttt{MC\_Step10\_Test\_Needed} = \texttt{TRUE}$

grd3 : $\texttt{Heart\_State} = \texttt{KO}$

then

act1 : $\texttt{Disease\_step9} := \texttt{Dextrocardia}$

end

Event *Rhythm_test_FALSE_Step11* $\widehat{=}$

extends *Rhythm_test_FALSE_Step11*

any

rate

where

grd1 : $(\forall \texttt{l} \cdot \texttt{l} \in \{\texttt{II}, \texttt{V1}, \texttt{V2}\} \Rightarrow \texttt{PP\_Int\_equidistant(l)} = \texttt{FALSE} \vee$
$\texttt{RR\_Int\_equidistant(l)} = \texttt{FALSE} \vee$
$\texttt{RR\_Interval(l)} \neq \texttt{PP\_Interval(l)})$
$\vee$
$\texttt{P\_Positive(II)} = \texttt{FALSE}$

grd2 : $\texttt{rate} \in 1 \,..\, 300$

grd5 : $\texttt{rate} \in 1 \,..\, 300$

then

act1 : $\texttt{Sinus} := \texttt{No}$

act2 : $\texttt{Heart\_Rate} := \texttt{rate}$

act3 : Heart_State := KO

act4 : Disease_step11 :∈ {Atrial_Premature_Beats, Ventricular_Premature_Beats, Nodal_Premature_Beats, Bradyarrhythmias, Narrow_QRS_Tachycardias, Wide_QRS_Tachycardias}

end

Event *Step11_N_QRS_Tachycardia_Regular* $\widehat{=}$

Narrow QRS achycardia Regular....

refines *Step11_N_QRS_Tachycardia*

when

grd1 : $Sinus = No$

grd2 : $Heart\_State = KO$

grd3 : $Heart\_Rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$

grd4 : $Disease\_step11 = Narrow\_QRS\_Tachycardias$

grd5 : $NW\_QRS\_Tachycardia\_RT\_State = Regular$

then

act1 : $Distease\_step11\_NW\_QRST :\in \{Sinus\_Tachycardia, AVNRT, AF\_Fixed\_AV\_Conduction, AT\_Paroxysmal\_NParoxysmal, WPW\_Syndrome\_OCMT\}$

end

Event *Step11_N_QRS_Tachycardia_Irregular* $\widehat{=}$

Narrow QRS achycardia Irregular....

refines *Step11_N_QRS_Tachycardia*

when

grd1 : $Sinus = No$

grd2 : $Heart\_State = KO$

grd3 : $Heart\_Rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$

grd4 : $Disease\_step11 = Narrow\_QRS\_Tachycardias$

grd5 : $NW\_QRS\_Tachycardia\_RT\_State = Irregular$

then

act1 : $Distease\_step11\_NW\_QRST :\in \{Atrail\_Fibrillation, AF\_Variable\_AV\_Conduction, AT\_Variable\_AV\_Block, Multifocal\_Atrial\_Tachycardia\}$

end

Event *Step11_W_QRS_Tachycardia_Regular* $\widehat{=}$

Wide QRS achycardia Regular....

refines *Step11_W_QRS_Tachycardia*

when

grd1 : $Sinus = No$

grd2 : $Heart\_State = KO$

grd3 : $Heart\_Rate \in 1 \,..\, 300 \setminus 60 \,..\, 100$

grd4 : $Disease\_step11 = Wide\_QRS\_Tachycardias$

grd5 : $NW\_QRS\_Tachycardia\_RT\_State = Regular$

then

act1 : $Distease\_step11\_NW\_QRST :\in \{Ventricular\_Tachycardia, Supraventricular\_Tachycardia, AVNRT, WPW\_Syndrome\_Orthodromic, Sinus\_Tachycardia, Atrial\_Tachycardia, AF\_Fixed\_AV\_Conduction, WPW\_Syndrome\_Antidromic\}$

end

Event *Step11_W_QRS_Tachycardia_Irregular* $\widehat{=}$
Wide QRS achycardia Irregular....

refines *Step11_W_QRS_Tachycardia*

when

grd1 : $Sinus = No$
grd2 : $Heart\_State = KO$
grd3 : $Heart\_Rate \in 1 \mathrel{..} 300 \setminus 60 \mathrel{..} 100$
grd4 : $Disease\_step11 = Wide\_QRS\_Tachycardias$
grd5 : $NW\_QRS\_Tachycardia\_RT\_State = Irregular$

then

act1 : $Distease\_step11\_NW\_QRST :\in \{AF\_BBB\_WPW\_Synd\_Antidromic,$
$AF\_Variable\_AV\_Conduction\_BBB\_WPW\_Synd\_Anti, Torsades\_de\_pointes\}$

end

END